Southeastern Geology: Volume 22, No. 4
December 1981

Edited by: S. Duncan Heron, Jr.

Abstract

Academic journal published quarterly by the Department of Geology, Duke University.

SOUTHEASTERN GEOLOGY

PUBLISHED AT DUKE UNIVERSITY DURHAM, NORTH CAROLINA

VOL. 22 NO. 4 DECEMBER, 1981

SOUTHEASTERN GEOLOGY

PUBLISHED QUARTERLY

AT

DUKE UNIVERSITY

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SOUTHEASTERN GEOLOGY

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LITHOSTRATIGRAPHY, DEPOSITIONAL ENVIRONMENTS AND TECTONIC FRAMEWORK OF THE EOCENE NEW BERN FORMATION AND OLIGOCENE TRENT FORMATION, NORTH CAROLINA

By

Gerald R. Baum
Exxon Production Research Company
P. O. Box 2189
Houston, Texas 77001

ABSTRACT

The late Eocene New Bern Formation consists of three facies: a basal, calcareous quartz arenite; a sandy, fine, pelecypod-mold biomicrosparrudite; and a sandy, medium to coarse, pelecypod-mold biomicrosparrudite. The basal calcareous quartz arenite facies represents intertidal deposition. The overlying sandy, fine, pelecypod-mold biomicrosparrudite facies represents deposition in a higher energy surf zone. The sandy, medium to coarse, pelecypod-mold biomicrosparrudite facies represents deposition on a sandy continental shelf at depths of 7-40 m.

The Oligocene Trent Formation consists of three facies: a basal, poorly washed, sandy, echinoid biosparite; a sandy, pelecypod-mold biomicrudite; and a barnacle, pelecypod-mold biosparrudite. The basal, poorly washed, sandy, echinoid biosparite facies represents intertidal deposition. The sandy, pelecypod-mold biomicrudite facies was probably deposited on a sandy continental shelf at depths of 7-40 m. The overlying barnacle, pelecypod-mold biosparrudite facies represents the regressive phase of deposition.

The internal morphology (progradation/onlap) of depositional sequences is controlled principally by rates of clastic influx and/or biologic productivity. The New Bern Formation (and probably the Trent Formation) is characterized by onlap because of low clastic influx and low biologic productivity. Basin tectonics principally controls lithofacies development and geometry.

The faunal change between the late Eocene New Bern Formation and the underlying middle Eocene Castle Hayne Limestone indicates a cooling trend near the Eocene/Oligocene boundary. Published Rb/Sr dates indicate that the boundary is between 34.8 and 34.1 my.

INTRODUCTION

In 1978, Baum *et al.* established a litho-space and chronostratigraphic framework for the middle Eocene to early Miocene formations of North Carolina. Subsequently, Baum (1980) published a detailed petrographic study of the lithofacies of the middle Eocene Castle Hayne Limestone. This article is intended to complete the lithostratigraphic framework of Baum et al. (1978c) by presenting the detailed petrography of the lithofacies of the late Eocene New Bern Formation and the Oligocene Trent Formation.

Tectonic Setting

The seaward, monoclinal dip of the Coastal Plain strata of North Carolina is disrupted by two sets of prominent parallel faults: the Grangers and Carolina faults which trend NE-SW; and the Cape Fear and Neuse faults which trend NW-SE (Figure 1). These faults have been periodically active throughout much of the deposition of the Mesozoic and Cenozoic sediments of North Carolina (Harris *et al.* 1979b; 1979c).

PETROGRAPHY

The petrologic and point count procedures have been previously outlined (Baum, 1980). All samples consisted primarily of calcite (less than 4 mole percent Mg); however, some aragonite was present in the form of dust rings lining the external molds of molluscs.

Carbonate Terminology and Classification

With a few modifications, Folk's (1959; 1962; 1965; 1973; 1974) carbonate classification and terminology are used in this report. In proposing his classification, Folk (1959) deviated from standard grain size parameters and established 1 mm as the boundary between arenite and rudite size allochems. Considering this arbitrary, some authors have shifted the boundary back to 2 mm (Harris, 1978). However, the 1 mm boundary was best suited for rocks studied in this report. Mollusc shell fragments, principally pelecypods, tend to cluster around 2 mm; thus, it was difficult to establish accurately the mean size in consolidated sediments. The 1 mm boundary seems to be a more natural break with allochemical clasts; however, a major drawback is that very few facies could be established using the 1 mm boundary. To differentiate between abraded shell material (higher energy regime), the rock name was prefixed by <u>fine</u> if the allochems ranged from 1-4 mm and <u>medium to coarse</u> if the allochems were greater than 4 mm. This procedure was useful in establishing facies in which the energy regimes were slightly different, as indicated by the degree of abrasion, but the allochemical composition remained the same. This scheme was only necessary in differentiating the lithofacies of the New Bern Formation.

Folk (1965) proposed the term microspar for aggraded micrite 4- 60 in size and listed the criteria for distinguishing it from interparticle spar cement (see also Bathurst, 1971). He also proposed the term pseudospar for material similar to microspar but greater than 60 µ ; however, he proposed a dual origin for pseudospar: pseudospar could be formed by the aggrading neomorphism of either organic skeletons or micrite. The dual origin of pseudospar serves no useful function in carbonate calssification; therefore, the term will not be used in this report. The term microspar is used to denote only aggraded micrite greater than 4 µ .

Porosity terminology is after Choquette and Pray (1970).

NEW BERN FORMATION

Outcrops of the New Bern Formation are confined to an area lying between the Neuse and Trent rivers (Figure 1). The structural alignment of this formation appears to differ from that of the Castle Hayne Limestone and the Trent Formation. The depositional strike appears to be oriented 45^{0} to the strikes of the other formations and may represent the second order tectonic stage of Brown *et al.* (1972). Outcrops are essentially limited to central Craven County and central and western Jones County.

Only three localities along the Neuse River reveal the lower disconformable contact of the New Bern Formation (CR-7, CR-8, CR-9). At these localities, the New Bern Formation rests disconformably on the Castle Hayne Limestone. It appears that the New Bern Formation does not disconformably overlap any formations older than the Castle Hayne Limestone. The New Bern Formation is disconformably overlain by the Trent Formation and the Yorktown Formation (CR-R, J-8).

The New Bern Formation consists of three facies, in ascending stratigraphic order: calcareous quartz arenite; sandy, fine, pelecypod-mold biomicrosparrudite; and sandy, medium to coarse, pelecypod-mold biomicrosparrudite.

Calcareous Quartz Arenite Facies

Distribution. This facies is a moderate to well consolidated, very pale orange (10 YR 8/2) to light gray (N 7) unit. The major framework component is quartz sand with a few pelecypods, now as molds. Bedding is typically massive; however, it is frequently

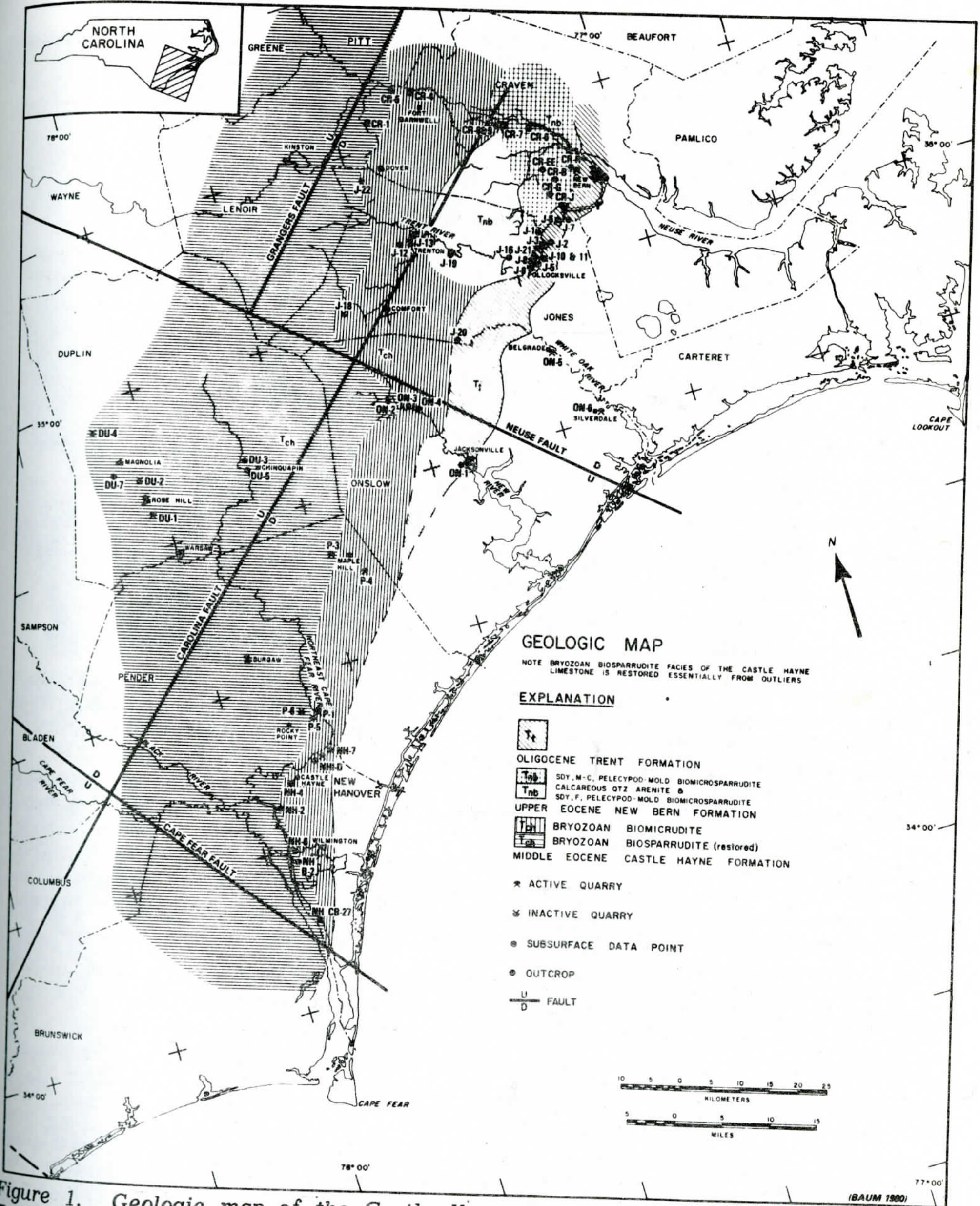


Figure 1. Geologic map of the Castle Hayne Limestone, New Bern Formation and Trent Formation, North Carolina (modified from Baum et al., 1978 and Harris et al., 1979).

disrupted by *Callianassa* burrows. In outcrop, this facies is poorly exposed and occurs at three localities (J-5, J-16, J-19).

Along the Neuse River (CR-7, CR-8, CR-9), the New Bern Formation lies disconformably on the Castle Hayne Limestone. At these localities, the calcareous quartz arenite facies can be considered absent. However, this facies appears to thicken along an east-west axis that passes through the vicinity of New Bern.

Petrography. This lithology is framework supported by well sorted, very fine to fine, monocrystalline quartz sand with minor amounts of heavy minerals (Table 1; Plate 1 a-

Table 1. Mean point count and insoluble residue data for the calcareous quartz arenite facies of the New Bern Formation.

INSOLUBLE RESIDUE ANALYSIS BY WEIGHT PERCENT (n=5)

	Mean (%)	Standard Deviation (%)
Carbonate	53.2	13.5
Sand Size	38.0	12.6
Silt + Clay Size	8.8	4.5

POINT COUNT DATA (n=5)

Mean Total Rock Porosity 9.2%

	(%)	(%)
ALLOCHEMS		
Echinoids		3.8
Pelecypods		3.8
Moldic Porosity	3.6	
Shell	0.2	
Red Algae		3.2
Unknown		3.2
Foraminifera		1.2
Shell	1.0	
Intraparticle Micrite	0.2	
Bryozoans		0.4
Intraparticle Micrite	0.2	
Shell	0.2	
Peloids		0.4
TERRIGENOUS		
Quartz		31.8
Heavy Minerals		0.2
MATRIX		
Microspar		38.6
Micrite		7.4
POROSITY		
Vug		4.2
Channel		1.4
ORTHOCHEMICAL		
Glauconite		0.4
Total		100.0

b). Associated allochems consist of echinoids, pelecypods as molds, encrusting red algae (***Archaeolithothamnium***), foraminifera, bryozoans and peloids. The red algae generally outline the pelecypod molds (Plate 1c-d).

The matrix is typically very fine to fine, blocky microspar with minor amounts of micrite (Plate 1a-b). Glauconite is the only orthochemical constituent and is rare.

The mean carbonate content (soluble in HCl) of this lithofacies is 53.2% with a standard deviation of 13.5% (carbonate content ranges from 34% to 69%). Thus, this facies ranges from a calcareous arenite to a very sandy microsparite. The variation in carbonate content is probably related to reworking and deposit feeding by littoral organisms (see Pryor, 1975) or corrosion of quartz by calcite.

If the terrigenous fraction is recalculated to 100%, quartz is 99% of the terrigenous fraction. Since the quartz is framework supported and micrite or microspar is always present, this lithology is designated a calcareous quartz arenite.

Sandy, Fine, Pelecypod-Mold Biomicrosparrudite Facies

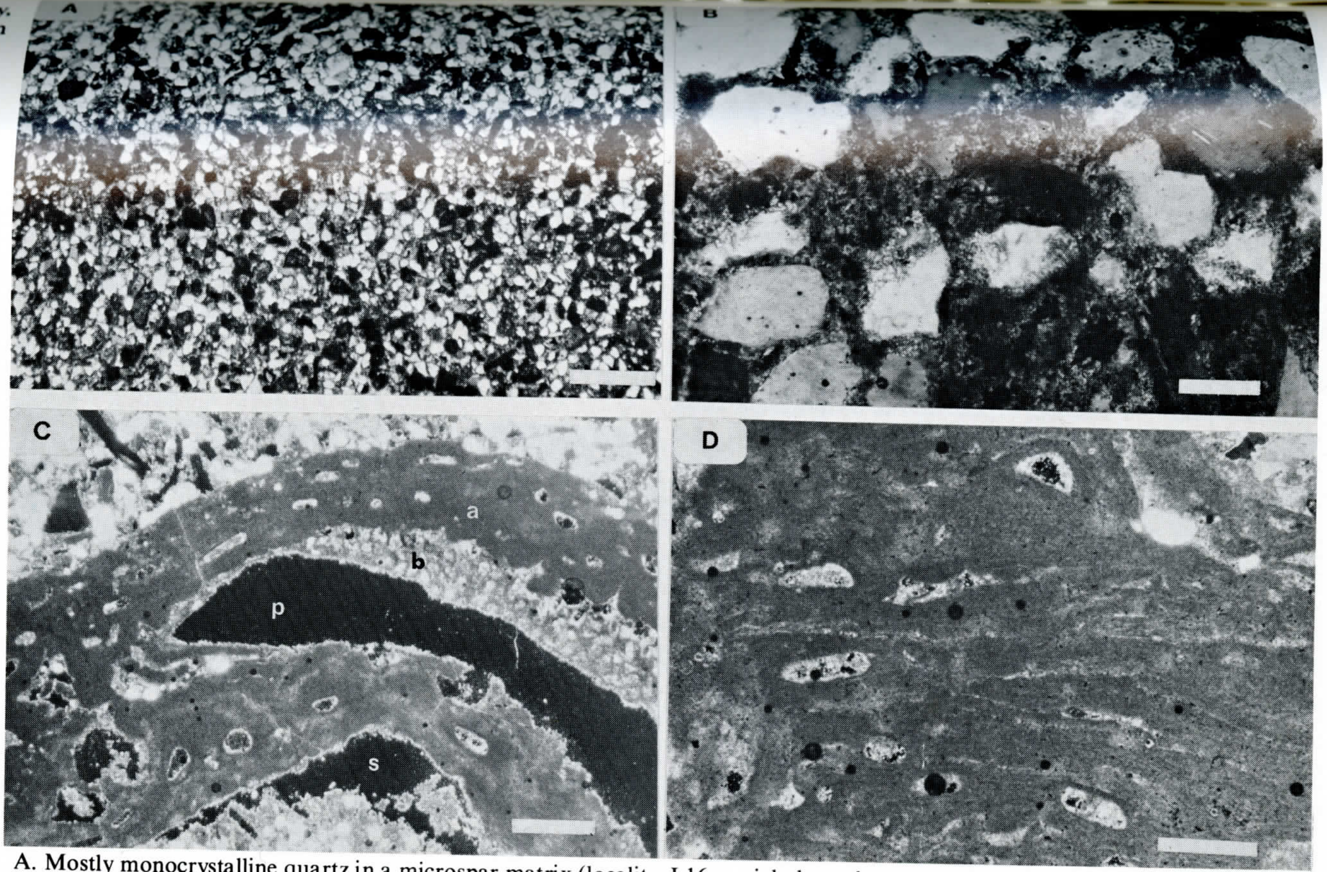
Distribution. This lithofacies is typically moderate to well consolidated, very pale orange (10 YR 8/2) to light gray (N 7) and characterized by abraded pelecypods 1 to 4 mm to size. Moderate angle planar cross-bedding is common (Plate 2d). *Callianassa* burrows frequently cut across the laminae of the cross-bedding (Plate 2a). The pelecypods are well sorted by size and now occur as molds.

This facies only outcrops at one locality (J-16) where it interfingers with the lower calcareous quartz arenite facies: however, it interfingers with the overlying sandy, medium to coarse, pelecypod-mold biomicrosparrudite facies in several cores (CR-R, CR-J, CR-G, CR-B).

Like the calcareous quartz arenite facies, this facies can be considered absent at the Neuse River localities (CR-7, CR-8, CR-9) where the New Bern Formation rests disconformably on the Castle Hayne Limestone. Likewise, this facies appears to thicken along an east-west axis that passes through New Bern.

Petrography. The dominant framework component is abraded pelecypods, approximately 2 mm in size (Table 2; Plate 2). Other common allochems include echinoids

Plate 1:
Calcareous quartz arsenite facies of the New Bern Formation.



A. Mostly monocrystalline quartz in a microspar matrix (locality J-16; x-nichols; scale equals 1.0 mm).
B. Monocrystalline quartz in micritic microspar (locality CR-R; x-nichols; scale equals 0.1 mm).
C. *Archaeolithothamnium* (a) encrusting bryozoan (b) encrusted pelecypod (p) which now occurs as a mold; note shelter porosity (s) (locality J-19; x-nichols; scale equals 1.0 mm).
D. *Archaeolithothamnium;* note characteristic lense or layer shaped conceptacles (locality J-19; x-nichols; scale equals 0.5 mm).

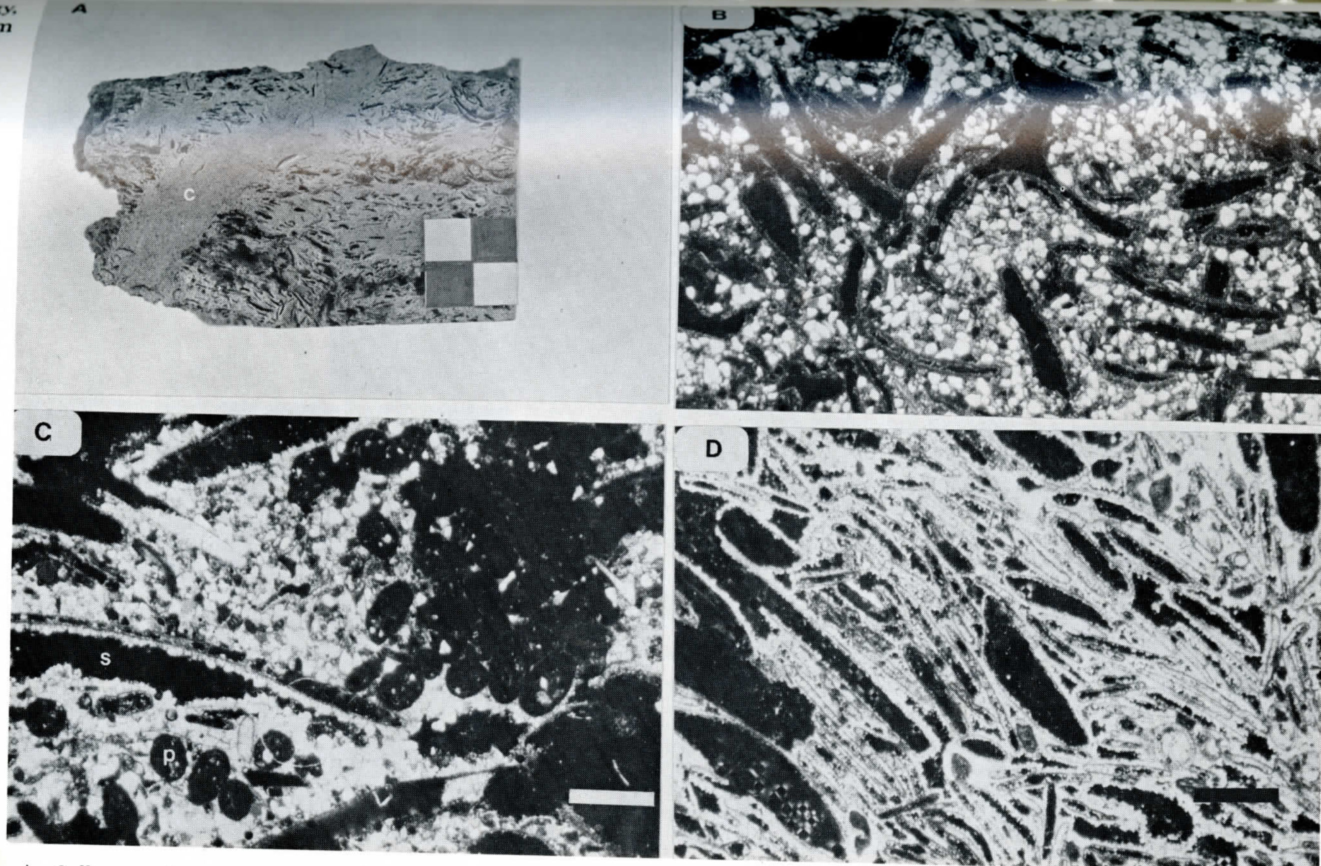


Plate 2.
Sandy, fine, pelecypod-mold biomicrosparrudite facies of the New Bern Formation

A. *Callianassa* burrow (c) cutting across bedding plane (locality J-16; scale graduated in cm).
B. Abraded pelecypods as molds in a sandy, microsparite matrix (locality CR-R; x-nichols; scale equals 1.0 mm).
C. Peloids (p) and pelecypods as molds in a sandy, microsparite matrix; note shelter porosity (s) (locality CR-B; x-nichols; scale 1.0 mm).
D. Cross-bedded, abraded pelecypods as molds; note absence of quartz sand and microspar (locality CR-G; x-nichols; scale 1.0 mm).

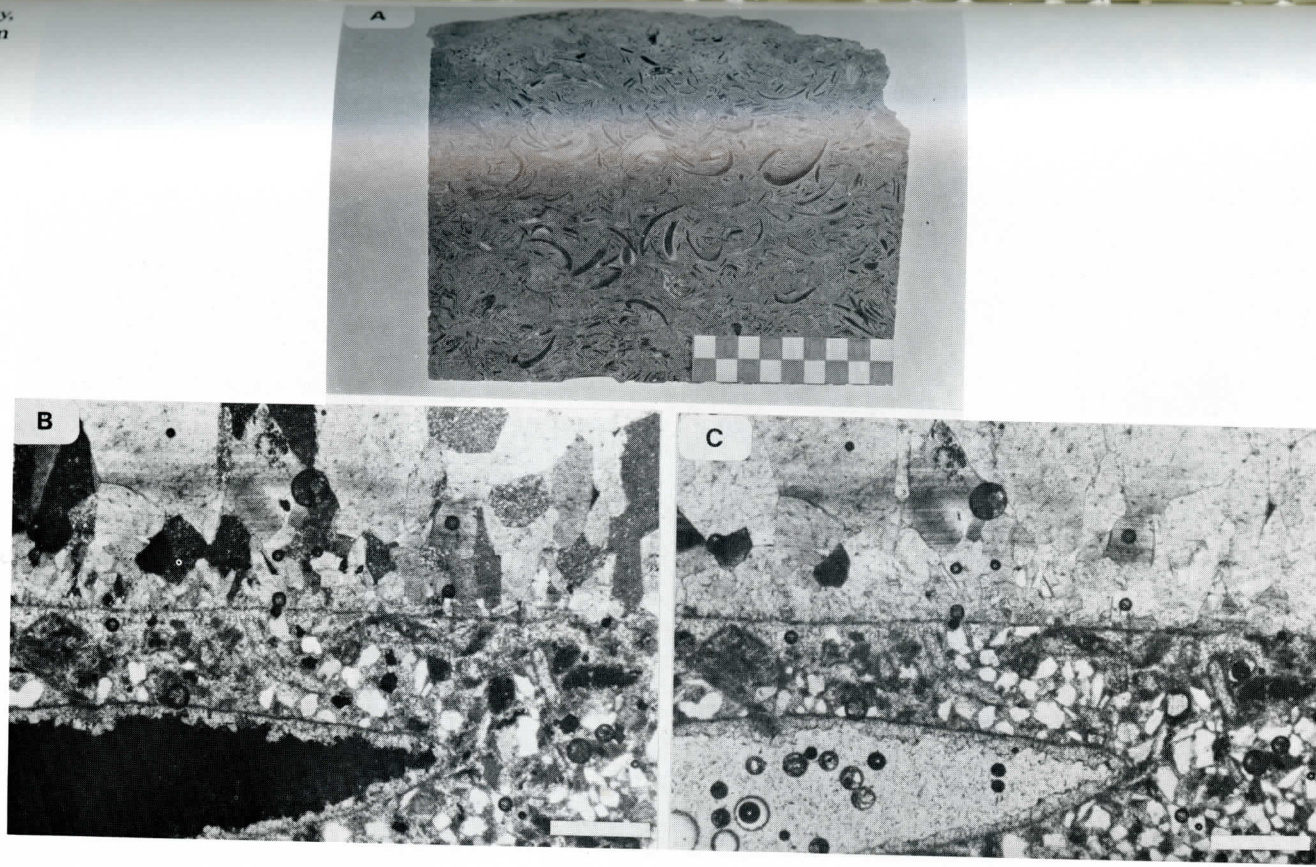


Plate 3.
Sandy, medium to coarse, pelecypod-mold biomicrosparrudite facies of the New Bern Formation.

A. Slab cut just below the disconformity with the overlying Trent Formation; note micrite filling some of the molds (locality CR-R; scale graduated in cm).
B. Pelecypods as molds and neomorphed shell; note remnant shell structure (locality CR-G; x-nichols; scale equals 0.5 mm).
C. Same as B, uncrossed nichols

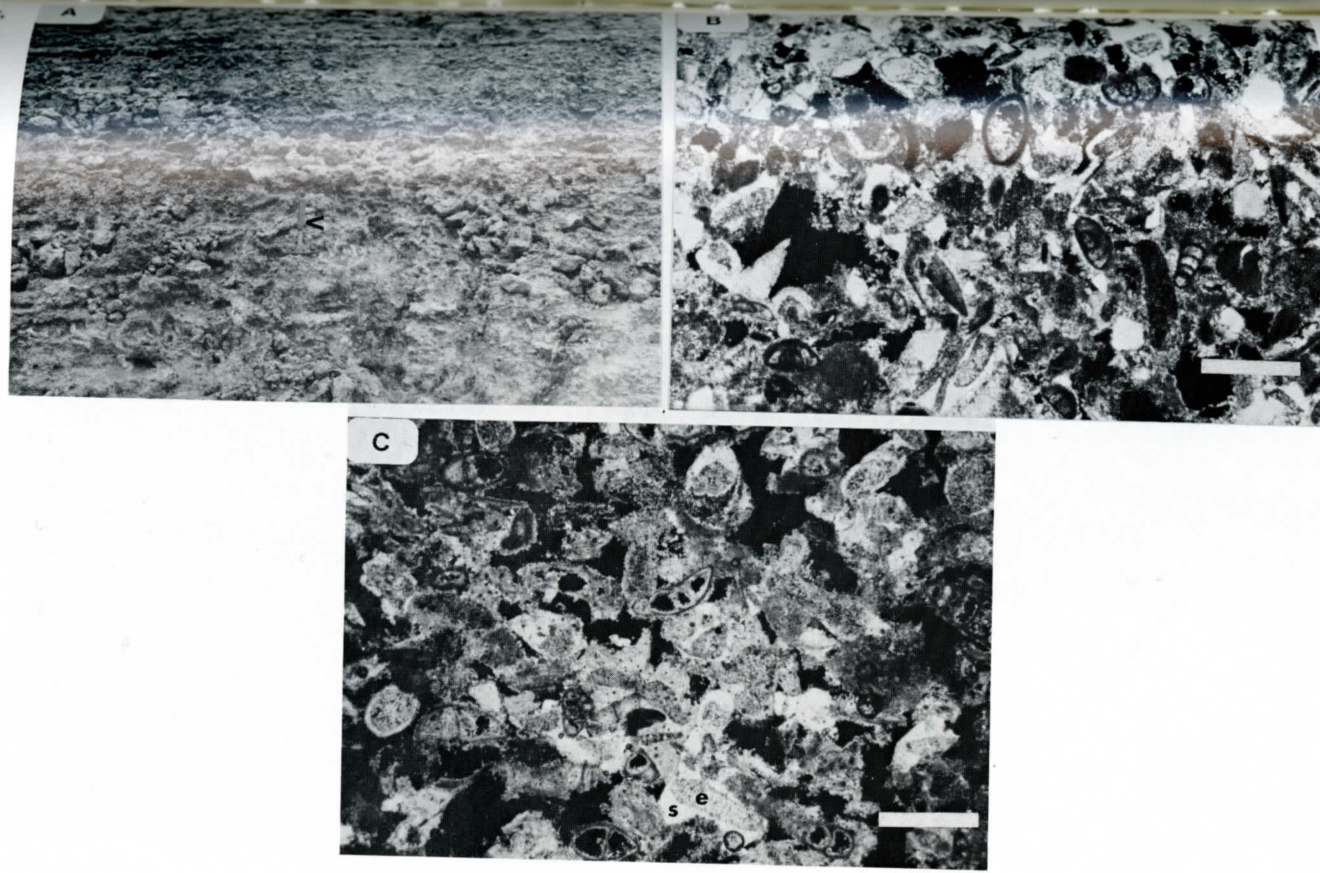


Plate 4.
Poorly washed, sandy, echinoid biosparite facies of the Trent Formation.

A. Low angle planar cross-bedding; *Callianassa* burrows slightly to right to hammer (locality J-21; hammer is scale).
B. Foraminifera and echinoids cemented principally by syntaxial overgrowths on enchinoids (locality J-10; x-nichols; scale 0.5mm).
C. Foraminifera and echinoids (e) cemented lightly by syntaxial overgrowths (s) on echinoids (locality CR-R; x-nichols; scale 0.5mm).

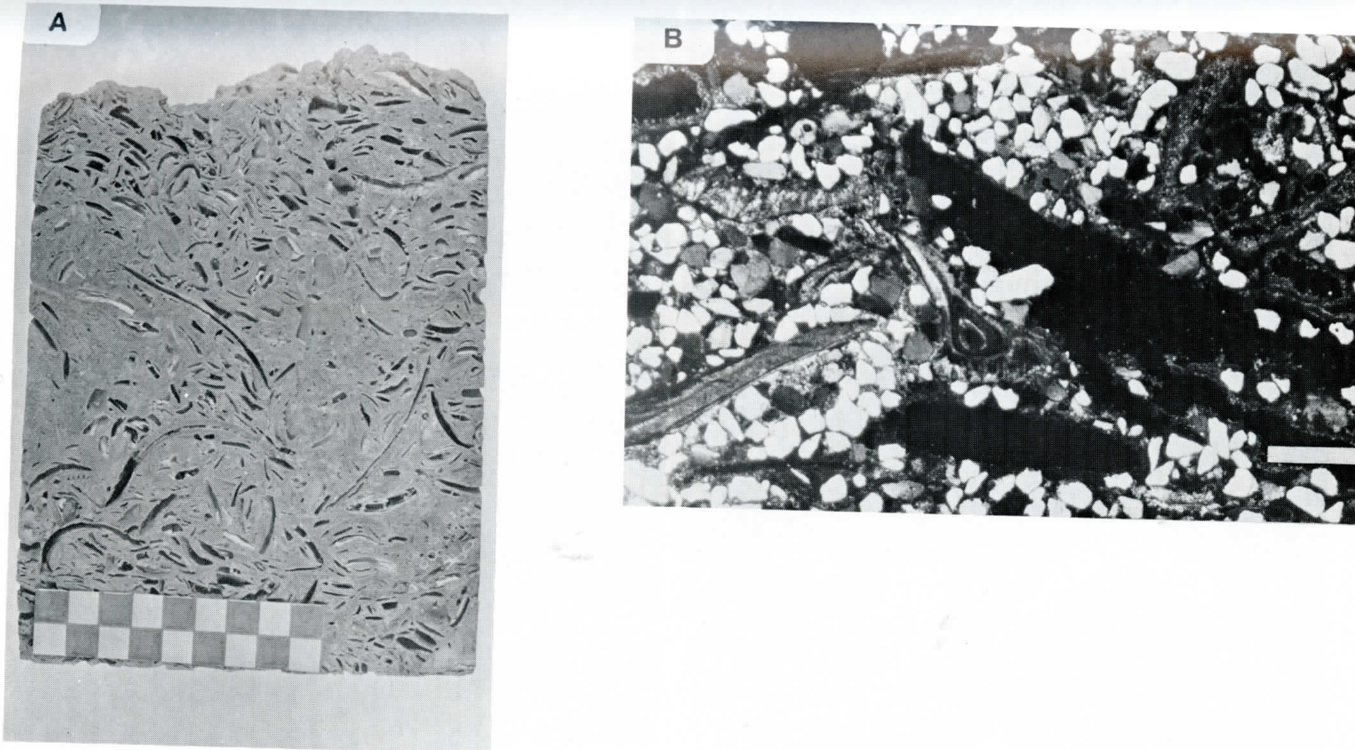


Plate 5.
Sandy, pelecypod-mold biomicrudite facies of the Trent Formation.

A. Slab; note some aragonite in molds (locality J-21; scale graduated in cm).
B. Pelecypods as molds and barnacles (b) in a sandy, micrite matrix (locality J-21; x-nichols; scale equals 1.0 mm).

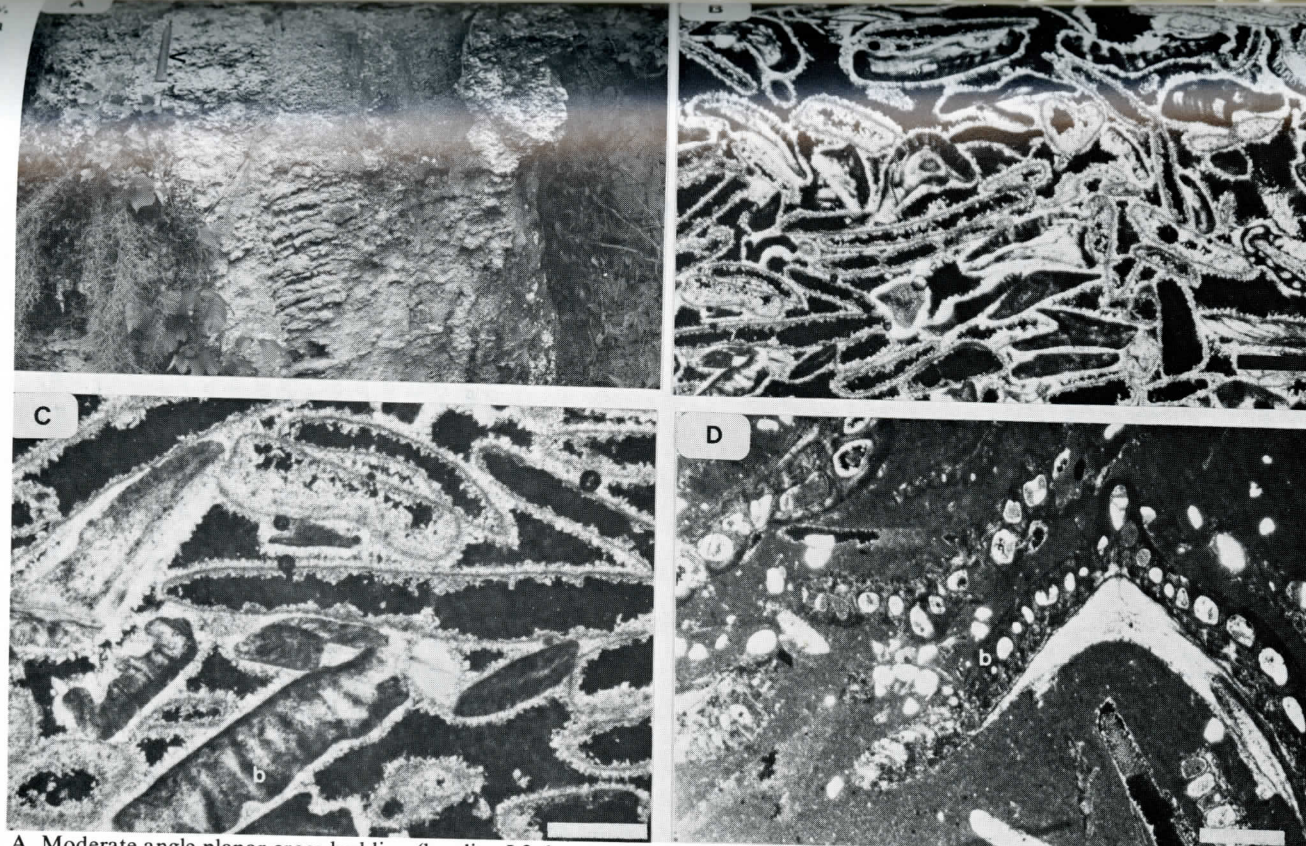


Plate 6.
Barnacle, pelecypod-mold biosparrudite facies of the Trent Formation.

A. Moderate angle planar cross-bedding (locality J-2; hammer is scale).
B. Pelecypods as molds and barnacles (b) lightly cemented by dogtooth spar (locality J-2; x-nichols; scale equals 1.0 mm).
C. Pelecypods as molds and barnacles (b) lightly cemented by dogtooth spar (locality J-2; x-nichols; scale equals 0.5 mm).
D. Lower Miocene Belgrade Formation; note inner and outer laminae of barnacles (b) which characterize the *Balanus (Balanus) concavus* stock. The presence of these barnacles can be used to differentiate the Oligocene Trent Formation from the overlying Belgrade Formation (locality ON-5; x-nichols; scale equals 1.0 mm).

Table 2. Mean point count and insoluble residue data for the sandy, fine, pelecypod-mold biomicrosparrudite facies of the New Bern Formation.

INSOLUBLE RESIDUE ANALYSIS BY WEIGHT PERCENT (n=15)

	Mean (%)	Standard Deviation (%)
Carbonate	63.8	13.6
Sand Size	28.9	12.6
Silt + Clay Size	7.3	2.3

POINT COUNT DATA (n=15)

Mean Total Rock Porosity 40.7%

	(%)	(%)
ALLOCHEMS		
Pelecypods		28.1
Moldic Porosity	21.8	
Shell	5.9	
Moldic Spar	0.4	
Peloids		1.5
Echinoids		1.1
Unknown		0.8
Foraminifera		0.5
Barnacles		0.5
Bryozoans		0.3
Gastropods		0.1
Ostracods		T
Serpulids		T
Bone		T
TERRIGENOUS		
Quartz		12.9
Heavy Minerals		T
Detrital Phosphate		T
Feldspar		T
MATRIX		
Microspar		26.1
Micrite		7.0
CEMENT		
Interparticle Spar		1.8
POROSITY		
Channel		11.9
Interparticle		4.0
Vug		3.0
ORTHOCHEMICAL		
Glauconite		0.5
Total		100.1

and peloids. The aragonitic pelecypods and gastropods now occur as molds.

The matrix consists principally of fine to medium, blocky microspar with minor amounts of micrite. When present, interparticle spar consists of medium dogtooth spar. The terrigenous component is predominantly well sorted, very fine, monocrystalline quartz sand with minor amounts of heavy minerals, feldspar and detrital phosphate. Glauconite is a minor orthochemical constituent.

This lithofacies varies from a pelecypod-mold biosparrudite to a poorly washed, sandy, pelecypod-mold biosparrudite to a sandy, pelecypod-mold biomicrosparrudite (Plate 2b-d). As cross-bedding increases, sand and microspar content decrease (Plate 2d). Since the mean point count data indicate that the mean lithology is a sandy, pelecypod-mold biomicrosparrudite, this lithofacies is so designated. However, the characteristic that separates this lithofacies from the overlying facies, which is also a sandy, pelecypod-mold biomicrosparrudite lithology, is the abundance of abraded pelecypods. To differentiate between these two similar lithofacies, this lithofacies is prefixed with the modifying term fine to indicate that the allochems (pelecypods) are abraded and range in size from 1 to 4 mm.

Sandy, Medium-Coarse, Pelecypod-Mold Biomicrosparrudite Facies

Distribution. This facies is a massive, dense, well consolidated, light gray (N 7) to medium light gray (N 6) unit (Plate 3a). It is dominated by generally unabraded pelecypods which now occur as molds. The dominant form is *Callista*. The fauna also contains *Crassatella* cf. *C. Alta*, *Chlamys* aff. *C. cawcawensis*, *Calyptraea*, *Lucinia*, *Panopea*, *Glycymeris* and *Ostrea*. The pelecypods occur as articulated and disarticulated valves. Generally, when disarticulated, the valves are concave down. *Panopea*, a burrowing pelecypod, is almost always found articulated and in life position.

Although mined extensively at New Bern for rock aggregate, this facies has a very limited outcrop. It outcrops in Craven (RC-6, CR-7, CR-8, CR-9) and Jones (J-

Table 3. Mean point count and insoluble residue data for the sandy, medium-coarse, pelecypod-mold biomicrosparrudite facies of the New Bern Formation.

INSOLUBLE RESIDUE ANALYSIS BY WEIGHT PERCENT (n=27)

	Mean (%)	Standard Deviation (%)
Carbonate	65.5	8.5
Sand Size	25.1	7.8
Silt + Clay Size	9.4	2.0

POINT COUNT DATA (n=25)

Mean Total Rock Porosity 32.6%

	(%)	(%)
ALLOCHEMS		
Pelecypods		31.3
Moldic Porosity	23.7	
Shell	6.8	
Moldic Spar	0.9	
Peloids		3.3
Bryozoans		2.0
Intraparticle Spar	1.0	
Shell	0.6	
Intraparticle Microspar	0.4	
Intraparticle Porosity	T	
Intraparticle Chert	T	
Unknown		1.3
Echinoids		1.2
Foraminifera		0.5
Shell	4.0	
Intraparticle Microspar	0.1	
Barnacles		0.2
Serpulids		T
Ostracods		T
Gastropods		T
Red Algae		T
Bone		T
TERRIGENOUS		
Quartz		14.5
Heavy Minerals		0.1
Detrital Phosphate		T
Feldspar		T
MATRIX		
Microspar		25.4
Micrite		10.2
POROSITY		
Vug		4.7
Channel		4.2
ORTHOCHEMICAL		
Glauconite		0.9
	Total	99.8

5) counties. It does not appear to outcrop south of the Trent River. This facies is frequently confused with the Cretaceous Rocky Point Member of the Peedee Formation.

Petrography. The framework is dominated by pelecypods, now as molds (Table 3; Plate 3). Other common allochems include peloids, bryozoans and echinoids. The matrix is predominantly very fine to coarse, generally fine, blocky microspar with minor amounts of micrite. Micrite tends to be more common than microspar toward the base of the facies. Cement occurs only as intraparticle dogtooth spar, principally within pelecypod molds. The terrigenous component is principally fine to very fine, well sorted, monocrystalline quartz sand with minor amounts of heavy minerals, detrital phosphate and feldspar. Glauconite occurs as peloids.

TRENT FORMATION

The Trent Formation appears to be confined to an area lying between the Neuse and New rivers (Figure 1). It outcrops extensively along the Trent River from New Bern to within 0.7 km of Pollocksville. At New Bern, the Trent Formation is represented by a compressed 1 m section; however, along an axis parallel to the White Oak River, the section thickens and extends updip. Thus, the Trent Formation appears to lie within a structural basin delineated by the Neuse and New rivers.

The Trent Formation lies disconformably on the New Bern Formation at two localities (CR-R, J-8). The upper boundary of the Trent Formation is marked by disconformities with the Yorktown Formation (CR-R) and the Waccamaw Formation

Table 4. Mean point count and insoluble residue data for the poorly washed, sandy, echinoid biosparite facies of the Trent Formation.

INSOLUBLE RESIDUE ANALYSIS BY WEIGHT PERCENT (n=7)

	Mean (%)	Standard Deviation (%)
Carbonate	69.3	10.2
Sand Size	21.9	9.7
Silt + Clay Size	8.9	1.7

POINT COUNT DATA (n=7)

Mean Total Rock Porosity 28.0%

	(%)	(%)
ALLOCHEMS		
Echinoids		13.0
Unknown		8.0
Pelecypods		3.1
Moldic Porosity	2.1	
Shell	1.0	
Bryozoans		2.4
Shell	2.0	
Intraparticle Porosity	0.3	
Intraparticle Micrite	0.1	
Foraminifera		1.9
Shell	1.0	
Intraparticle Spar	0.4	
Intraparticle Micrite	0.4	
Barnacles		0.9
Ostracods		0.3
Red Algae		T
Bone		T
TERRIGENOUS		
Quartz		14.9
Detrital Phosphate		0.1
Heavy Minerals		T
MATRIX		
Micrite		19.3
Microspar		2.6
CEMENT		
Interparticle		7.9
POROSITY		
Interparticle		21.7
Channel		3.9
ORTHOCHEMICAL		
Glauconite		0.1
Total		100.1

(ON-1). Although cores drilled at the Belgrade quarry (ON-5) reveal little due to poor recovery in unconsolidated sediments, the samples indicate a phosphatized surface several meters below the quarry floor. These samples also indicate that the lower Miocene Belgrade Formation lies disconformably on the barnacle, pelecypod-mold biosparrudite facies of the Oligocene Trent Formation.

The Trent Formation consists of three facies, in ascending stratigraphic order: poorly washed, sandy, echinoid biosparite; sandy, pelecypod-mold biomicrudite and barnacle, pelecypod-mold biosparrudite.

Poorly Washed, Sandy, Echinoid Biosparite Facies

Distribution. This facies occurs as a friable to moderately consolidated, very pale orange (10 YR 8/2) to pale yellowish orange (10 YR 8/6) unit. The fauna includes the pelecypods *Chlamys trentensis*, *Pecten* aff. *P. perplanus poulsoni* (not *P. elixatus*) and *Anomia*; bryozoans, echinoids and the barnacle *Solidobalanus (Hesperibalanus)* which is generally attached to the pectens. Sedimentary structures include low angle planar cross-bedding and burrows of the ghost shrimp *Callianassa* (Plate 4a).

This facies lies disconformably on the New Bern Formation at two localites (CR-R, J-8). At New Bern (CR-R), this facies is represented by a compressed 0.3 m section; however, along the Trent River, this facies thickens and interfingers with the overlying, sandy, pelecypod-mold biomicrudite facies at several localites (J-11, J-21). The poorly washed, sandy, echinoid biosparite facies cannot be traced south of the Trent River.

Petrography. The dominant identifiable allochems are echinoids (Table 4; Plate 4); however, because of the abraded nature of most of the allochems, the percent of unknown type is high. Other common allochems include pelecypods, bryozoans, foraminifera and barnacles. The matrix includes very fine, blocky microspar with minor amounts of micrite. Interparticle cement is predominantly syntaxial overgrowths on echinoid fragments (Plate 4b-c). Minor amounts of fine to medium interparticle dogtooth spar occurs. The terrigenous fraction is dominated by well sorted, very fine to fine, monocrystalline quartz sand with minor amounts of detrital phosphate and heavy minerals. Glauconite is a minor constituent.

Sandy, Pelecypod-Mold Biomicrudite Facies

Distribution. This facies occurs as a massive, dense, well lithified, very pale orange (10 YR 8/2) to light gray (N 7) unit (Plate 5a). The fauna is dominated by molluscs which now occur principally as molds. The fauna includes: ***Mercenaria*, *Conus*, *Panopea*, *Glycymeris*, *Calyptraea*** and vermetid gastropods. ***Panopea***, a burrowng pelecypod, occurs articulated and in life position. Although many of the pelecypods are disarticulated, the fauna appears to represent a life assemblage that has undergone little or no transport. Superficially, this facies resembles the sandy, medium-coarse, pelecypod-mold biomicrosparrudite facies of the New Bern Formation; however it can be differentiated from the New Bern Formation by the presence of ***Mercenaria***, an Oligocene to Recent genus (Cox et al., 1969).

At New Bern (CR-R), this facies is represented by a compressed 0.2 m section. At this locality, this facies is characterized by ***Turritella*** gastropod molds and a lack of quartz sand. Along the Trent River, this facies appears to thicken and become sandier. The increased sand content is due to the fact that the Trent Formation overlaps the New Bern Formation further updip and lower in the section, thus deriving additional sand from the sandier and less consolidated portions of the New Bern Formation. Along the Trent River, this facies interfingers with the lower, poorly washed, sandy, echinoid biosparite facies (J-11, J-21) and the overlying barnacle, pelecypod-mold biosparrudite facies (J-1). An outcrop near Jacksonville (ON-1) indicates that this facies had a wide distribution.

Petrography. The dominant framework components are pelecypods which occur principally as molds (Table 5; Plate 5). Other common allochems include gastropods as molds and barnacles. The matrix is predominantly micrite with minor amounts of fine to medium, blocky microspar. The terrigenous component is predominantly well sorted, coarse to very fine, generally fine, monocrystalline quartz sand with minor amounts of detrital phosphate and heavy minerals.

Barnacle, Pelecypod-Mold Biosparrudite Facies

Distribution. This facies consists of friable to moderately consolidated, very pale orange (10 YR 8/2), grain supported pelecypods and barnacles. The pelecypods now occur as molds. The barnacle *Solidobalanus (Hesperibalanus)* occurs as opercular, lateral and basal disc plates. The abundance of opercular plates suggests that the barnacles were transported from their life site; however, the lack of abrasion indicates a short transport history. Unlike the barnacles, the pelecypods show evidence of severe abrasion, and range in size from 1 to 4 mm. Typically, this facies exhibits moderate to high angle, planar cross-bedding (Plate 16a).

Like the lower two facies of the Trent Formation exposed at New Bern (CR-R), this facies is represented by a compressed 0.4 m section; however, along the Trent River, this facies thickens and interfingers with the lower, sandy, pelecypod-mold biomicrudite facies (J-1).

Petrography. The dominant framework components are barnacles and pelecypods (Table 6; Plate 6). Other common allochems include peloids and echinoids. The pelecypods and gastropods occur predominantly as molds. The matrix consists of minor amounts of very fine to medium, generally fine, microspar with some micrite. Cement occurs as medium to coarse, generally medium, interparticle dogtooth spar. The terrigenous component is predominantly well sorted, medium to very fine, detrital phosphate, feldspar and heavy minerals.

Table 5. Mean point count and insoluble residue data for the sandy, pelecypod-mold biomicrudite facies of the Trent Formation.

INSOLUBLE RESIDUE ANALYSIS BY WEIGHT PERCENT (n=12)

	Mean (%)	Standard Deviation (%)
Carbonate	68.5	9.3
Sand Size	27.2	11.8
Silt + Clay Size	4.3	4.0

POINT COUNT DATA (n=8)

Mean Total Rock Porosity 33.8%

	(%)	(%)
ALLOCHEMS		
Pelecypods		31.3
Moldic Porosity	26.2	
Moldic Spar	2.8	
Shell	2.4	
Gastropods		3.0
Moldic Porosity	2.6	
Shell	0.3	
Intraparticle Micrite	0.1	
Barnacles		2.0
Unknown		1.4
Echinoids		0.4
Ostracods		0.1
Peloids		0.1
Serpulids		T
Foraminifera		T
TERRIGENOUS		
Quartz		23.2
Detrital Phosphate		0.8
Heavy Minerals		T
MATRIX		
Micrite		26.1
Microspar		6.8
POROSITY		
Vug		5.0
ORTHOCHEMICAL		
Glauconite		T
Total		100.2

Table 6. Mean point count and insoluble residue data for the barnacle pelecypod-mold biosparrudite facies of the Trent Formation.

INSOLUBLE RESIDUE ANALYSIS BY WEIGHT PERCENT (n=8)

	Mean (%)	Standard Deviation (%)
Carbonate	89.1	12.7
Sand Size	8.0	
Silt + Clay Size	2.9	

POINT COUNT DATA (n=8)

Mean Total Rock Porosity 32.8%

	(%)	(%)
ALLOCHEMS		
Pelecypods		28.5
Moldic Porosity	17.6	
Shell	9.9	
Moldic Spar	1.0	
Barnacles		19.4
Peloids		2.8
Echinoids		1.1
Unknown		0.5
Gastropods		0.4
Moldic Porosity	0.3	
Shell	0.1	
Bryozoans		0.1
Foraminifera		0.1
Serpulids		T
TERRIGENOUS		
Quartz		5.4
Detrital Phosphate		0.1
Feldspar		T
Heavy Minerals		T
MATRIX		
Microspar		11.4
Micrite		2.1
POROSITY		
Interparticle		12.7
Vug		1.3
Channel		0.9
CEMENT		
Interparticle		13.2
Total		100.0

The fauna of the New Bern and Trent formations are typical of mollusc dominated, sandy, continental shelves. Their respective basinward biomicrudite facies contain essentially the same fauna; however, the New Bern Formation is dominated by the pelecypod ***Callista***; whereas, the Trent Formation is dominated by the Oligocene to Recent pelecypod ***Mercenaria***. Otherwise, their faunal elements are very similar and contain a number of overlapping and extant genera: ***Glycymeris***, ***Conus***, ***Panopea***, ***Calyptraea*** and ***Chlamys***. Vermetid gastropods, in places, are more common in the Trent Formation. The low diversity and moldic nature of the faunas constrain detailed paleoecologic analyses; however, the distribution of extant genera suggests a marine biogeographic zone, not unlike the present continental shelf of North Carolina.

Likewise, their respective lithofacies are similar and represent similar depositional enviornments. The basal part of the New Bern Formation is represented by a calcareous quartz arenite and a sandy, fine, pelecypod-mold biomicrosparrudite. The basal Trent Formation is represented by a poorly washed, sandy, echinoid biosparite. These basal lithologies are characterized by ***Callianassa*** burrows, abraded allochems and low to moderate angle, planar cross-bedding. These sedimentary structures are strongly suggestive of intertidal deposition (Weimer and Hoyt, 1964; Davies ***et al.***, 1971; Howard and Reineck, 1972; Wunderlock, 1972; Howard ***et al.***, 1973). The common occurrence of ***Archaeolithothamnium*** in the calcareous quartz arenite facies of the New Bern Formation also suggests intertidal deposition (Taylor, 1960). The basal stratigraphic position of these lithologies would seem to confirm their intertidal nature. The calcareous nature of the basal calcareous quartz arenite facies of the New Bern Formation suggests increased deposit feeding by littoral organisms (Pryor, 1975). The lack of a basal quartz arenite facies in the Trent Formation is a reflection of a lack of a source of sand. Lithified carbonates act as clastic sediment traps; thus, where the Trent Formation rests disconformably on the consolidated sandy, medium to coarse, pelecypod-mold biomicrosparrudite facies of the New Bern Formation, the basal lithology is an echinoid biosparite. Where the disconformity lies further updip, the echinoid biosparite derives additional sand from the poorly consolidated and sandier lithologies of the New Bern Formation.

The stratigraphic position and the fauna of the downdip and basinward biomicrudites of the New Bern and Trent formations suggest lower neritic deposition on a warm temperate, sandy continental shelf. The mollusc suite of these formations is similar to Thorson's (1957) ***"Venus"*** community which characterizes sandy bottom, open marine continental shelves at depths of 7-40 m. The lack of ***Mercenaria*** in the New Bern Formation is a reflection of the Eocene age of the unit; however, ***Callista*** appears to have been the ecologic equivalent of ***Mercenaria*** during the Eocene.

The upper barnacle, pelecypod-mold biosparrudite facies of the Trent Formation represents the regressive phase. The high angle planar cross-bedding, lack of terrigenous material (sand size), abraded nature of the pelecypods and abundance of barnacles suggest depths within the surf zone. The increased number of barnacle opercular plates suggests that the barnacles were reworked from the basal lithologies; however, the lack of abrasion suggests a short transport history.

The dramatic change, as well as diversity, between the fauna of the middle Eocene Castle Hayne Limestone (see Baum, 1980; Kier, 1980) and the late Eocene New Bern Formation indicates a deterioration of the tropical climate which characterized deposition of the Castle Hayne Limestone. The change in fauna and diversity do not appear to be related to terrigenous influx, for equivalent non-clastic formations of South Carolina (Santee Limestone/Cross Formation; see Baum ***et al.***, 1979; 1980; Kier, 1980) display the same faunal relationships. This faunal boundary perhaps correlates with possible Antarctic glaciation and/or development of the psychrosphere in the late Eocene (Shackleton and Kennett, 1975; Savin ***et al.***, 1975; Kennett and Shackleton, 1976). Foster (1974) noted a dramatic change in echinoid faunas across this boundary. Kier (1980) noted the same change in the echinoid fauna of the Carolinas. Approximately 29 different species are found in the Castle Hayne Limestone; whereas, none have been found in the New Bern Formation (although the equivalent formation in South Carolina, the Cross Formation, has yielded ***Periarchus lyelli***, ***Marstia subrostrata*** and ***Protoscutella plana***, apparently the only echinoid species to transcend the boundary.)

Faunally, the New Bern Formation is more similar to the Oligocene Trent Formation than to the underlying Castle Hayne Limestone. Likewise, Vail and Mitchum (1979) now place the Priabonian (TE3) into the Tc supercycle, rather than Tb, suggesting a stronger depositional affinity with the Oligocene. As pointed out by Kennett and Shackleton (1976), this cooling trend probably affected higher latitudes earlier, thus creating diachronous usage of the Eocene/Oligocene boundary. Apparently, in the Carolinas, the cooling trend occurred at the Bartonian/Priabonian boundary, rather than at the Eocene/Oligocene boundary (also see Hickman, 1976; 1980). Published Rb/Sr glauconite dates (Harris *et al.*, 1979a; Fullagar *et al.*, 1980) indicate that the boundary (or glaciation) occurred between 34.8 and 34.1 my in the Carolinas.

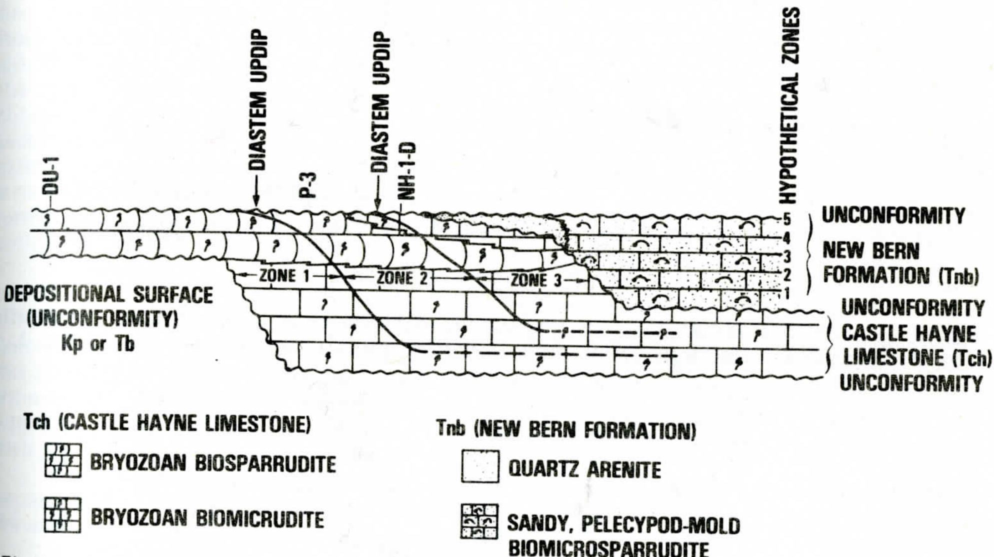


Figure 2. Cross section perpendicular to Carolina fault illustrating sequence morphology of Castle Hayne Limestone and New Bern Formation. Localities from Figure 1. Zone 1 = Cubitostrea lisbonensis/Santeelampas oviformis (TE 2.2); Zone 2 = Cubitostrea sellaeformis (TE 2.3); Zone 3 = partially Periarchus lyelli (?TE 2.4).

BASIN TECTONICS

The middle Eocene Castle Hayne Limestone represents a prograding supercycle (Tb) characterized by an offlapping sequence of toplapping and downlapping clinoforms (Figure 2) (sequences after Vail and Mitchum, 1979) whereas, the overlying New Bern and Trent formations are characterized by onlap. Within the Castle Hayne Limestone, two distinct sequences and a possible third can be recognized (in ascending stratigraphic order): *Cubitostrea lisbonensis/Santeelampas oviformis* (TE2.2/P12); *Cubitostrea sellaeformis* (TE2.3/P13); and an unzoned upper sequence (?T2.4/P14) which appears to straddle the Bartonian/Priabonian boundary (see Worsley and Turco, 1979; Zullo, 1979; Zullo and Baum, 1979, in press; Harris *et al.*, 1979a; Fullagar *et al.*, 1980) (zones modified from Baum *et al.*, 1979; 1980; and Kier, 1980). However, the upper sequence may only represent local basin tectonics in proximity to the Cape Fear fault. Updip, the cycles are separated by diastems (Baum *et al.*, 1978c; 1979; 1980) and are the sites of local Dorag dolomitization (Baum *et al.*, 1978a, 1978b). Downdip, sedimentation was continuous, and physical evidence of the diastems is absent.

Prior to the deposition of the overlying New Bern Formation (TE3), major structural reorientation occurred in the depositional basin and appears to be concurrent with the development of the Southeast Georgia Embayment (Baum and Powell, 1979). The New Bern Formation is characterized by coastal onlap onto a dissected and faulted erosional Castle Hayne Limestone surface (Figure 2).

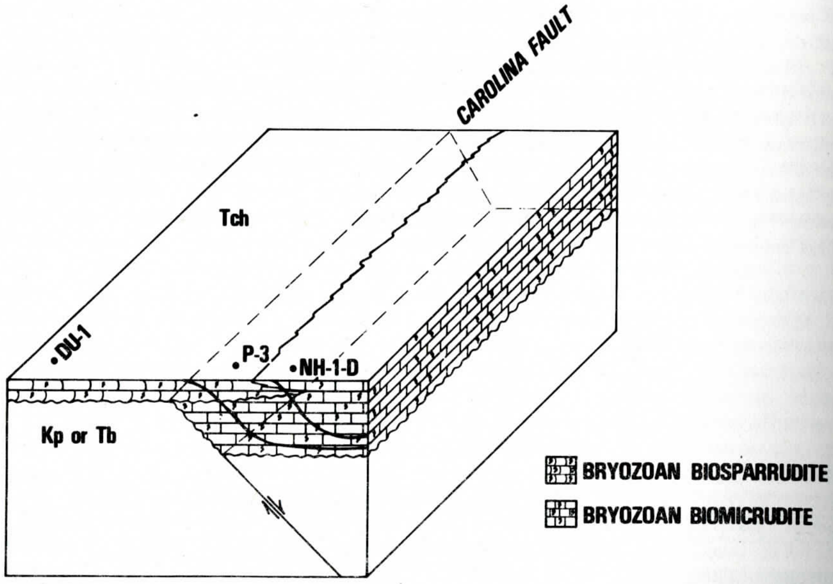


Figure 3. Oblique block diagram illustrating lithofacies development of the Castle Hayne Limestone. Uniform throw along Carolina fault. Localities from Figure 1.

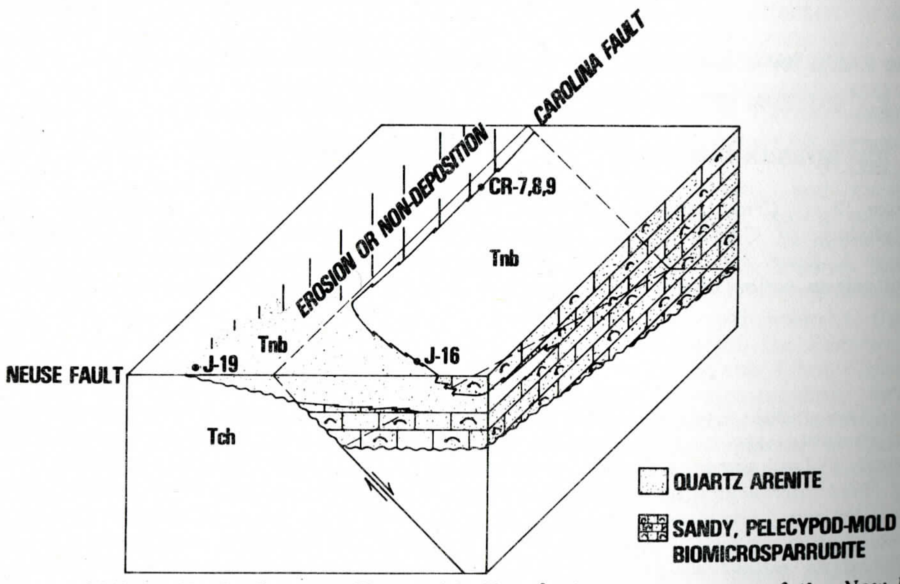


Figure 4. Oblique block diagram illustrating lithofacies development of the New Bern Formation. Differential throw along Carolina fault with downthrown block dipping to northeast. Localities from Figure 1.

The Tb supercycle (Castle Hayne Limestone) and TE3 cycle (New Bern Formation) are characterized by their lack of terrigenous sediments. The high rates of biologic productivity in a tropical environment appears to have controlled the progradation of the Castle Hayne Limestone (Tb); whereas, the New Bern Formation, deposited in a more temperate environment, is characterized by onlap due to low biologic productivity and low sediment influx. Tectonics, basin subsidence, and rate of sea level change do not appear to have controlled the internal sequence morphology (progradation/onlap). Basin tectonics did, however, control lithofacies development as well as lithofacies geometry. During deposition of the Castle Hayne Limestone, the Carolina fault created a broad, uniform shelf and slope (Figure 3). Thus, the transition from the shallower water bryozoan biosparrudite lithofacies to the deeper water bryozoan biomicrudite lithofacies mimics the trend of the Carolina fault (Baum, 1980). In the area of the Cape Fear fault, this trend appears to shift seaward, although subsequent erosion has blurred the relationships.

Prior to the deposition of the New Bern Formation, movement along the Carolina and Neuse faults constricted the basin of deposition; however, the amount of throw along the downthrown block was not uniform (Figure 4). The downthrown block dips to the northeast. Along the distal basin margin (northeast) parallel to the Carolina fault (localities CR-7, 8, 9), the shallower water lithofacies (quartz arenite) was not deposited, and the deeper water lithofacies (sandy, pelecypod-mold biomicrosparrudite) lies disconformably on the Castle Hayne Limestone. Along the proximal basin margin (southwest) near the juncture of the Carolina and Neuse faults (localities J-16, 19), the shallower water lithofacies is well developed. Because of the asymmetry of the basin, the transition from the shallower water lithofacies to the deeper water lithofacies is oblique to the Carolina fault, rather than parallel to it. This relationship is similar to sedimentation along modern capes where shallow water sedimentation is oblique to the main trend of the coast. This would explain then the change between the depositional strike of the Castle Hayne Limestone and New Bern Formation. Outcrops of the Trent formation are limited; however, there appear to have been no tectonic effects on sedimentation.

ACKNOWLEDGEMENTS

I am deeply grateful to Walter H. Wheeler and Daniel A. Textoris (University of North Carolina, Chapel Hill) for their interest, support and advice during the course of this research. W. Burleigh Harris and Victor A. Zullo (University of North Carolina, Wilmington) assisted in the field and offered many helpful suggestions. Martin Marietta Aggregates has patiently allowed me to work in their quarries and allowed access to their 2-inch exploratory cores.

This research was partically funded by grants from the North Carolina Department of Natural and Economic Resources, Sigma Xi and the Smith Fund of the University of North Carolina at Chapel Hill.

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CLAY MINERALOGY OF WEATHERING PROFILES FROM THE CAROLINA PIEDMONT

By

Patricia J. Loferski
U.S. Geological Survey
Reston, Virginia 22092

ABSTRACT

Twelve saprolite profiles that formed over various crystalline rocks from the Charlotte 1° by 2° quadrangle showed overall similarity in their clay mineralogy to depths of 6-45 m indicating control by the weathering process rather than by the rock type.

The amount of <4 µm clay ranged from about 3 percent in a few samples to about 70 percent near the top of a granite profile. Most samples contained 10-25 percent clay. Five profiles showed no variation in clay toward the top; three showed a progressive increase in clay caused by increased feldspar weathering; others showed irregular changes controlled by the mineralogy and the grain size in the saprolite.

Kaolinite and halloysite composed 75 percent or more of the <2 µm clay fraction of most samples. The ratio of kaolinite to halloysite ranged widely, from 95 percent kaolinite to 90 percent halloysite, and this was independent of depth. Halloysite was not found in two profiles. Clay-size mica was present in all profiles, and ranged from 5 percent in some samples to 75 percent over a sericite schist. Mixed-layer mica-smectite and mica-vermiculite were subordinate; discrete smectite and vermiculite were rare.

Profiles of saprolites used in making building brick showed varied grain-size distributions, and the <2 µm clays were predominantly kaolinite and mica, with as much as 20 percent halloysite.

The widespread occurrence and local abundance of halloysite indicate a continuously humid environment since the time of profile formation, because of the rapidity with which halloysite dehydrates irreversibly.

INTRODUCTION

Weathering of rocks in the southeastern United States has produced a deep zone of saprolite, or partly altered rock which retains the original texture and structure of the parent rock. The saprolites in the southeastern United States are thick and well developed; thus, they are of unique value for studying the clay mineralogy of weathered rock profiles.

This paper reports on the clay mineralogy and grain-size distributions of 12 saprolite profiles formed over a variety of crystalline rocks from the Charlotte 1° by 2° quadrangle, located in North Carolina and adjacent parts of South Carolina. The purpose of the study was to characterize the clay mineralogy of saprolites derived from a variety of rock types, and to determine how the clay mineralogy of the saprolites is related to the rocks from which they formed. The study was conducted as a part of the U.S. Geological Survey's investigation of the geology and mineral resources of the Charlotte 1° by 2° quadrangle. Some of the saprolite in the study area is used for making building brick, and in the production of kaolin, scrap mica, sand, and gravel. A map of the study area and sample locations are shown in figure 1.

Regional geologists have subdivided the Southern Appalachians into six northeast-trending geologic belts according to the similarity of rock types and the degree of metamorphism (Butler and Ragland, 1969; Sundelius, 1970; Overstreet, 1970; Fullager, 1971). These belts, all of which are found in the study area, are: 1) the Blue Ridge belt, a complex area of granitic gneiss, plutonic rock, and highly metamorphosed sedimentary and volcanic rock mostly of Proterozoic age; 2) the Brevard belt, a narrow

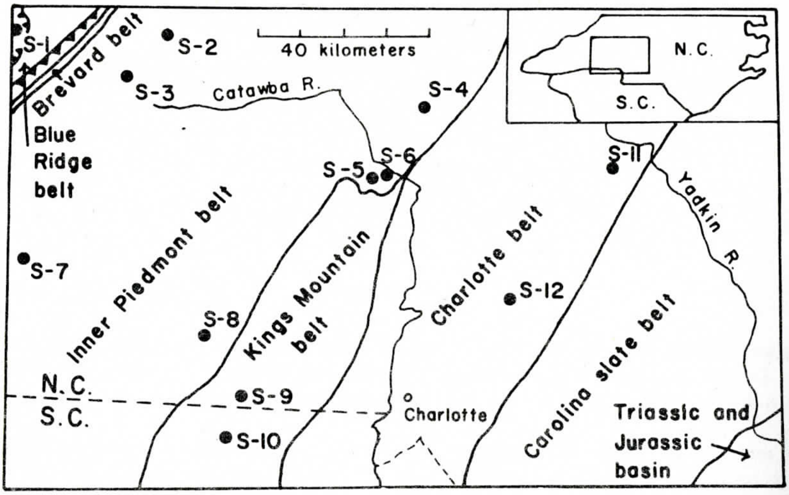

Figure 1. Map showing the study area and sample locations.

zone of low-grade metamorphic and cataclastic rocks of early Palezoic age; 3) the Inner Piedmont belt, consisting of well-foliated schist, gneiss, amphibolite, and large areas of augen and granitic gneiss, all of undetermined age; 4) the Kings Mountain belt, consisting of a wide variety of metasedimentary and metavolcanic rocks of variable metamorphic grade, some of which may be of early Paleozoic age; 5) the Charlotte belt, consisting of granitic plutons and other granitoid rocks of moderate metamorphic grade, of early Paleozoic age; and 6) the Carolina Slate belt, consisting of low-grade metamorphic sedimentary and volcanic rock of probable Paleozoic age. The southwest edge of a basin containing sedimentary rocks of Triassic and Jurassic(?) age occurs in the southeastern corner of the study area.

Previous weathering studies on saprolite and soil from the southeastern United States (Cady, 1950; Sand, 1956; Grant, 1962: Grant, 1964; Harriss and Adams, 1966; Wolff, 1967; Plaster and Sherwood, 1971; Gardner et al., 1978) and from other localities (Goldich, 1938; Dennen and Anderson, 1962; Parham, 1969a and b) have established a sequence of mineral stability during weathering. This sequence is the reverse of the crystallization sequence of minerals from an igneous melt. Those studies have also shown that the alkali and alkaline-earth elements are particularly mobile during weathering, and that the mobility of other common cations is more complex and variable.

The age of the saprolites of the southeastern United States is uncertain, and they may have formed as long ago as the Miocene (Plaster and Sherwood, 1971), or as recently as 1-2 million years ago (M. Pavich, oral commun., 1979).

The previous studies have been restricted to smaller numbers of samples or smaller geographic areas than the present study, or else they have emphasized the geochemistry rather than the mineralogy of saprolite. Little work has been done on the clay mineralogy of saprolite from the study area.

METHODS OF INVESTIGATION

A total of 106 samples were collected from 12 saprolite profiles that had formed over a variety of rock types: 1) pegmatite from the Blue Ridge belt; 2) granitic gneiss, garnetiferous granitic gneiss, mica gneiss, mica schist, and biotite-sillimanite schist from the Inner Piedmont belt; 3) pegmatite and Battleground (sericite) Schist from the Kings Mountain belt; and 4) Concord Syenite of Butler and Ragland (1969) and Salisbury Granite of Chayes (1952) from the Charlotte belt.

Most of the samples were collected from quarries where saprolite sections were well exposed, and others were collected from railroad and roadcuts. The exposed saprolite was commonly 12 or more meters thick; one section over a pegmatite-

Table 1. Location and rock type of saprolite profile samples.

Profile number	Parent rock type	Stratigraphic name	Color	Location	Number of samples	Interval sampled
Blue Ridge belt						
S-1	pegmatite		white to buff	Harris Mining Co., 1 km west of Linville Falls, N.C.	11	45m
Inner Piedmont						
S-2	granitic gneiss		medium gray	Face behind sanitary landfill, 2.5 km northwest of Lenoir, N.C.	12	18m
S-3	granitic gneiss		light red	Abandoned pit, 5 km north of Morganton, N.C.	5	6m
S-4	garnetiferous granitic gneiss		banded white and black	Statesville Granite Quarry, 0.5 km northwest of Statesville, N.C.	11	15m
S-5	granitic gneiss		light red and green	Shuford gold mine, 2.5 km southeast of Catawba, N.C.	5	7.5m
S-6	mica schist		light red	Railroad cut, 2.5 km southeast of Catawba, N.C. intersection Rte. 1833	8	10.5m
S-7	mica schist		buff to light green	Cut behind Grace Tabernacle Church, 6 km north of Rutherfordton, N.C.	8	10.5m
S-8	biotite-sillimanite schist		red	Railroad cut, 5 km southwest of Cherryville, N.C.	5	10.5m
Kings Mountain belt						
S-9	pegmatite		white to buff	King's Mtn. Mica Co., 3 km northeast of Grover, N.C.	11	15m
S-10	sericite schist	Battleground Schist	white to gray	Abandoned pit in S.C., 25 km southeast of Grover, N.C.	10	13.5m
Charlotte belt						
S-11	granite	Salisbury Granite of Chayes (1952)	red	Isenhour Brick & Tile Co., East Spencer, N.C.	7	9m
S-12	syenite	Concord Syenite of Butler and Ragland (1969)	buff to light red	Corriher Gravel Pit, 4.5 km southwest of Kannapolis, N.C.	13	18m

granodiorite, profile S-1, had an exceptional thickness of more than 45 m.

No residual boulders of fresh rock were found in any of the profiles sampled, and the basal contact with fresh rock was usually not seen.

Table 1 gives the approximate sample location, parent rock type, and number of samples in each profile. The profiles were sampled at 1.5 m intervals except in a few instances where it was not possible to obtain a sample at the designated interval. Samples were collected moist by digging several centimeters into the saprolite and were stored in tightly sealed plastic bags to preserve all hydrated phases.

Each sample was separated into sand, silt, and clay fractions for size analysis. A 100 g portion of each sample was disaggregated in a blender, and wet- then dry-sieved through a 230 mesh (62.5 μm) screen to separate sand (> 62.5 μm) from silt and clay. The clay-size fraction (<4 μm) was separated from the silt by settling in water. The sand and silt fractions were dried and weighed, andpercentages were obtained. The percentage of clay was obtained by subtracting the combined percentage of sand and silt from 100.

A split of each whole sample was oven dried, ground to pass a 170 mesh sieve, and pressed into a 29 mm-diameter wafer which was used for X-ray-diffraction analysis of the whole sample.

The clay fraction was prepared for X-ray-diffraction analysis by using an ultrasonic probe to disperse each sample in water, then the < 2 μm portion of each sample was separated by settling in water. A small amount of the < 2 μm portion was placed on a glass slide and the water was allowed to evaporate until the clay was almost dry. The slide was then stored in a humid environment to prevent dehydration of hydrous phases before X-ray-diffraction analysis.

Samples were run on a standard X-ray diffractometer using Cu $K\alpha_1$ radiation and a crystal monochromator. X-ray-diffraction traces were made of each < 2 μm clay sample: untreated, saturated with ethylene glycol, and heated at 350°C for at least half an hour. Clay minerals were identified by the methods described by Brown (1961)

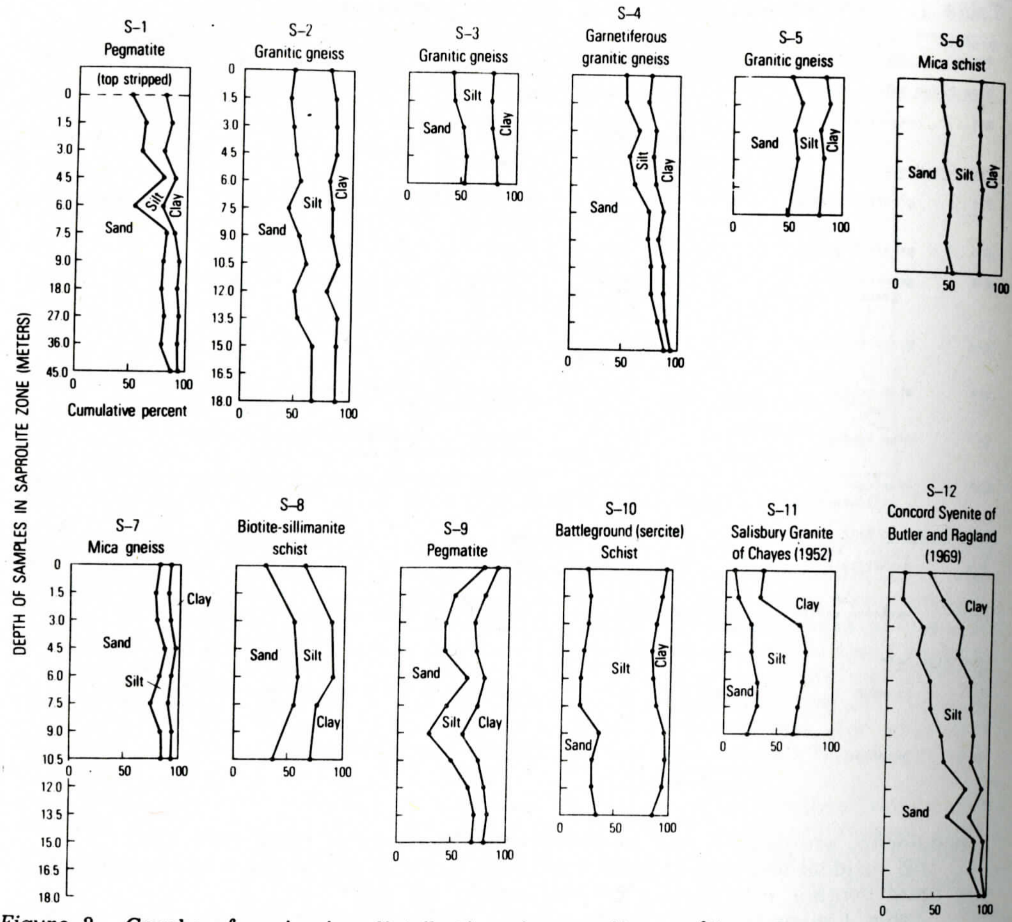

Figure 2. Graphs of grain-size distributions in saprolite profiles. Dots represent data points for individual samples. Sand > 62.5 μ m; silt 62.5-4 μ m; clay <4 μ m.

and Carroll (1970).

The ratios of clay-mineral abundances were determined by using an electronic planimeter to measure the appropriate peak areas on the X-ray-diffraction traces of the clay fractions. Proportions of mica and the mixed-layer clay were determined by the difference in the areas of the 10A peaks on 1) the X-ray trace of the ethylene glycol-treated samples, where only mica is at 10A, and 2) the X-ray trace of the heat-treated samples, where both mica and mixed-layer clay have 10A peaks. Proportions of kaolinite and halloysite were determined in a similar manner by the difference in the areas of the 7A peaks on the X-ray traces of 1) the ethylene glycol-treated samples where only kaolinite has a 7A peak, and 2) the heat-treated samples where both halloysite and kaolinite contributed to the intensity of the 7A peak. The amount of smectite or vermiculite was determined by measuring the area of the 14A peak of the untreated samples. The ratios are semiquantitative and are considered to represent relative rather than absolute values.

GRAIN-SIZE DISTRIBUTIONS

The grain-size distributions of the 12 profiles are shown in figure 2. The amount of <4 μm clay ranged from about 3 percent in a few samples to 70 percent near the top of Chayes' Salisbury Granite profile S-11. However, most samples contained 10-

25 percent clay, which is generally a characteristic amount in saprolite. Similar amounts of clay were found in saprolite from Virginia (Plaster and Sherwood, 1971).

Only two profiles had substantially more than the average amount of clay. In Chayes' Salisbury Granite, S-11, X-ray-diffraction analysis revealed a sudden drop in the amount of quartz in the saprolite near the top of the profile; this was accompanied by a corresponding relative increase in the amount of clay. In Butler and Ragland's Concord Syenite, S-12, increased feldspar weathering caused a large gradational increase in clay, from 5 percent at the base to 60 percent at the top. Thus, changes in the mineralogy and in the amount of weathering affected the clay content in some saprolites.

In addition to the Concord Syenite, two other profiles showed a progressive increase in the amount of clay toward the top: the pegmatite, S-1, and the garnetiferous granitic gneiss, S-4. In all three profiles increased feldspar weathering toward the top was indicated by X-ray-diffraction analysis, which showed progressively less feldspar and more clay minerals upward. Compared with the Concord Syenite profile, S-12, the increase in the other two profiles was much less pronounced.

Five profiles showed very little variation in clay content from the base to the top, which indicates a uniform amount of weathering throughout the entire thickness of those profiles. They were: the granitic gneisses, S-2, S-3, and S-5; the mica schist, S-6; and the mica gneiss, S-7.

Two other profiles showed fluctuations in clay content. In the pegmatite, S-9, the fluctuations are the result of inhomogeneous grain-size in the parent rock as observed at the outcrop. Thus, relatively finer grained areas weathered more thoroughly than coarser grained areas.

The other profile which showed fluctuation in clay proportion was the biotite-sillimanite schist, S-8. In that profile, the clay content decreased toward the middle of the profile, and this was correlated with a local increase in the amount of sillimanite. Sillimanite, which is resistant to weathering, is concentrated in the larger size fractions, so the clay content decreased by this difference.

The Battleground (sericite) Schist profile, S-10, had unusually large amounts of silt. The small amount of quartz relative to mica may have contributed to the small sand fraction; however, the reason for the small clay fraction is not apparent from the mineralogy, and may be the result of the local weathering environment.

Thus, no correlation was observed between the parent rock type and the amount of clay formed in the saprolites studied. Variations in the clay content within each saprolite profile was apparently determined by the degree of homogeneity of the parent rock's mineralogy and grain-size.

PROFILE MINERALOGY

Sand fraction

The sand fractions of the samples contained quartz, mica, and feldspars as the major constituents. Some of the grains were iron-stained. Some of the samples contained accessory minerals such as garnet, hornblende, and magnetite. The sand fractions often contained small, partly weathered rock fragments.

Clay fraction

The three predominant < 2 µm clay minerals in the saprolites, in decreasing order of abundance were: kaolinite, halloysite, and mica. Mixed-layer mica-smectite and mica-vermiculite were less abundant; discrete smectite and vermiculite were rare (figure 3).

Together, kaolinite and halloysite formed more than 75 percent of the <2 µm clay fraction of most samples. Halloysite is a hydrous mineral, similar in composition to kaolinite, which forms as a weathering product of feldspars. Haloysite will not be preserved if dehydration takes place, as the halloysite structure collapses irreversibly to a structure similar to that of kaolinite and the dehydrated halloysite is

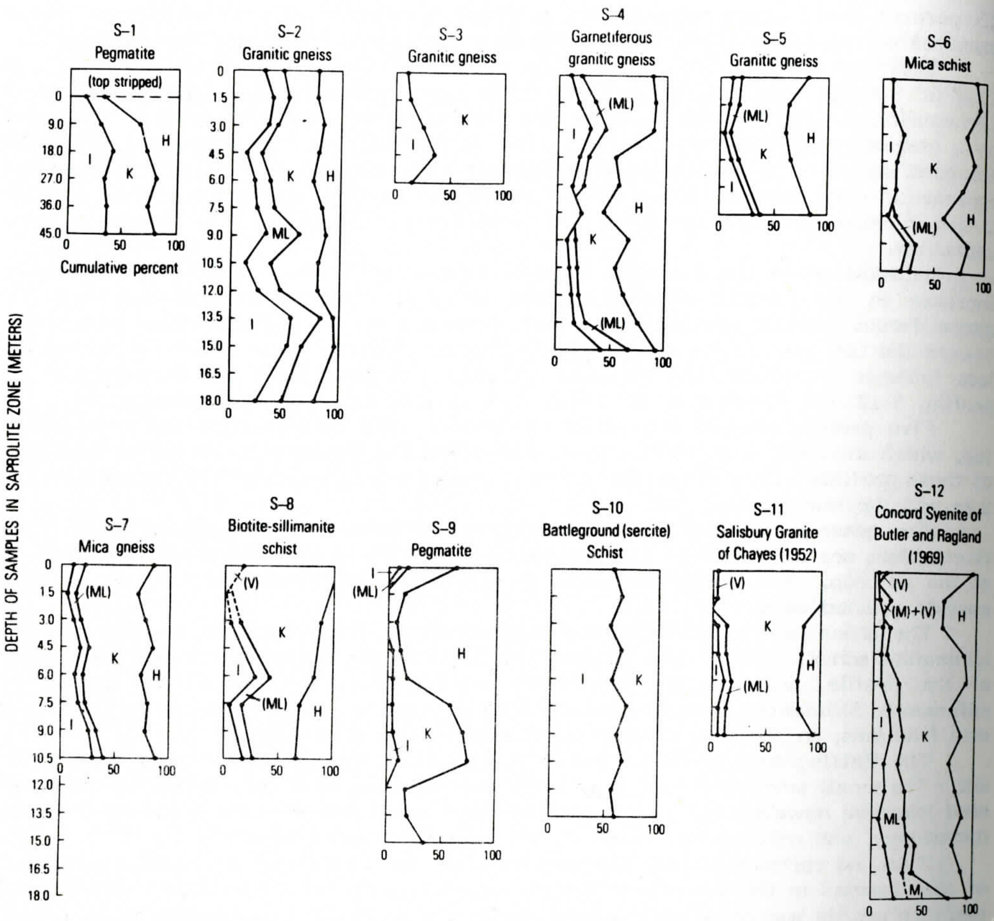

Figure 3. Graphs of the < 2 µm clay minerals in saprolite profiles. Dots represent data points for individual samples. Abbreviations used are: H = halloysite; K = kaolinite; M = mica; ML = mixed-layed clay; S = smectite; V = vermiculite.

indistinguishable from kaolinite on X-ray-diffraction traces. Kaolinite may form in the weathering profile from dehydrated halloysite, from other clay minerals, or directly from many primary minerals.

Kaolinite was found in all of the profiles, and halloysite was found in all except two, the granitic gneiss, S-3, and the Battleground (sericite) Schist, S-10. The absence of halloysite may indicate local dehydration in those two profiles.

Where they were both present, the ratio of kaolinite to halloysite varied widely, from 95 percent kaolinite in some samples over Chayes' Salisbury Granite, S-11, to 90 percent halloysite over the pegmatite, S-9. The ratio was independent of depth.

Clay-size mica ranged in abundance from 5 percent of the <2 µm clay fraction in some samples over the pegmatite, S-9, and the granite, S-11, to 75 percent over the sericite schist, S-10. Clay-size mica is a weathering product of muscovite and of potassium feldspar, and the mica may be further weathered to form kaolinite (Loughnan, 1969).

Mixed-layer clay minerals, found in most of the profiles, usually made up 5-10 percent of the <2 µm clay fraction. These minerals were found in two different forms. One was a randomly interlayered mica-smectite, characterized on X-ray-diffraction traces by expansion with ethylene glycol treatment, and collapse to 10A with heat treatment. This type of mixed-layer mineral was found in the granitic gneiss, S-5, the mica schist S-6, the mica gneiss, S-7, the Salisbury granite, S-11, and Butler and Ragland's Concord Syenite, S-12 (figure 3). This type of interlayering is generally common in weathered rocks, and is probably a weathering product of micaceous minerals, where some of the interlayer potassium has been removed and replaced by H_2O (Loughnan, 1969).

The other type of mixed-layer clay was an ordered mica-vermiculite (or vermiculite-like mineral in some clays). This mineral was characterized by X-ray diffraction peaks at about 24A and 12A; it did not expand with ethylene glycol saturation, and it collapsed to about 10A after heating. The mica-vermiculite was present in most of the biotite-rich granitic gneiss, S-2, the garnetiferous granitic gneiss, S-4, the biotite-sillimanite schist, S-8, and the top sample of the pegmatite, S-9 (figure 3). In the profiles, S-2, S-4, and S-8 mentioned above, the mica (biotite)-vermiculite is probably a weathering product of the original biotite in the parent rock. Biotite alters quickly to a mixed-layer biotite-vermiculite by partial replacement of the interlayer potassium by magnesium and H_2O (Loughnan, 1969).

In the pegmatite, S-9, the mica-"vermiculite" may be a weathering product of some of the muscovite, where some interlayer potassium has been replaced by aluminum (Loughnan, 1969).

The amount of mixed-layer clay was fairly constant from the base to the top in four profiles: The granitic gneisses, S-2 and S-5; the mica gneiss, S-7; and the garnetiferous granitic gneiss, S-4, except for one sample where mixed-layering was not detected. In four profiles, the mica schist, S-6, the biotite-sillimanite schist, S-8, Chayes' Salisbury Granite, S-11, and Butler and Ragland's Concord Syenite, S-12, mixed-layer clay was present at the base, and the amount fell to zero at depths of 3-7.5 m below the top of the saprolite zone.

Mixed-layer clays were absent in three of the profiles: The pegmatite, S-1, the granitic gneiss, S-3, and the Battleground (sericite) Schist, S-10. This may indicate locally more highly leached environments, or else the original rocks may not have contained sufficient calcium or magnesium for the formation of a smectite or vermiculite component.

Discrete vermiculite was present in only a few samples including the top sample of the biotite-sillimanite schist, S-8, the top two samples of the Salisbury Granite, S-11, and two samples of the Concord Syenite, S-12 (figure 3). The vermiculite was characterized by an X-ray-diffraction peak at 14A; it did not expland with ethylene glycol treatment, and it collapsed to 10A-11A after heat treatment. The vermiculite, or vermiculite-like mineral, is probably a weathering product of the micas.

Discrete smectite was present in small amounts in the Concord Syenite, and was not found as a discrete mineral in any of the other profiles. In the Concord Syenite, S-12, profile, smectite and the mixed-layer mica-smectite were probably formed by the weathering of micaceous minerals as described above.

The clay-mineral assemblages formed over the various rocks were similar, as nearly all the profiles were composed predominantly of kaolinite and halloysite. This similarity indicates control of the clay mineralogy by the weathering process rather than by the rock types studied. The removal of alkali and alkaline earth elements has led to the formation of the abundant kaolinite and halloysite. Any large differences which may have existed in the mineralogy or chemistry of the parent rocks are not reflected in the clay-mineral assemblages.

Grim (1968) stated that although the composition and texture of the parent rock is generally an important influence in the initial stages of weathering, the influence of the parent rock generally decreases as the duration of weathering increases. Furthermore, similar clay-mineral assemblages may form over different rock types if weathering proceeds for a long period of time.

In the profiles studied here, the duration of weathering is concluded to have been a more important control over the clay-mineral assemblages than the rock type, because similar clay-mineral assemblages have formed over different rocks.

ECONOMIC GEOLOGY

The saprolite in the study area is used for the production of a variety of industrial materials. Therefore, the economic utility of the saprolites in relation to the findings of this study is important to consider.

The major use of saprolite in the study area is in making building brick. Of the 12 profiles, 3 were obtained from open pits where the saprolite is or has been used for that purpose. These are profiles S-3, S-10, and S-11.

A comparison of the clay mineralogy of these profiles indicates that clay-size mica and kaolinite, in various ratios, were the dominant $<2\ \mu m$ clay minerals in the saprolite. Two of the three profiles, S-3 and S-10, contained no halloysite. Large amounts of halloysite may cause undesirable properties in ceramic materials, such as excessive shrinkage on drying (Grim, 1962), so its absence in those two profiles may have improved the quality of the saprolite for brick making. However, profile S-11, taken of saprolite currently used in making building brick, shows that as much as 20 percent of halloysite in the $<2\ \mu m$ clay fraction is not detrimental. The maximum tolerable amount of halloysite in building-brick material is not known.

Smectite is another clay mineral which is generally undesirable in ceramic material, because it dehydrates and may cause shrinkage or cracking of the ceramic product during firing (Grim, 1962). Smectite was absent from two of the profiles of brick material, S-3 and S-10. The third profile, S-11, contained a small amount of smectite as a component of the mixed-layer clay. This small amount, less than 5 percent of the $<2\ \mu m$ clay fraction, is apparently not a detriment.

The grain-size distributions of the three profiles of brick material were varied, indicating that there is a range of suitable grain-size in saprolite which may be used in making building brick. In profile S-10, the saprolite contained only small amounts of clay but large amounts of silt; in S-3 there was as much as 40-50 percent sand; and in profile S-11 there was 30 to 70 percent clay.

On the basis of their overall similarity in clay mineralogy and their grain-size distributions, it is possible that the saprolites of any of the profiles studied would be suitable for brick material.

However, this suitability can only be determined by making test bricks. The clay mineralogy cannot be used alone to predict suitability because the clay minerals form only a part of the saprolite; therefore, properties of the bricks are dependent on other characteristics of the saprolite as well. Grain-size distribution cannot be used alone to predict suitability because this study has shown that there may be a variety of suitable grain sizes.

Grimshaw (1971) summarized the characteristics of good brick material which are paraphrased as follows: it must contain some clay minerals so that it is plastic enough to mold easily and retain its shape wet and dry; it must also contain a large proportion of nonplastic material, such as quartz, feldspar, and rock fragments, so the shapes of the bricks will be preserved; it should vitrify easily at about 950-1100°C to form hard brick without excessive shrinkage or deformation. Many types of material may thus be used in making building bricks.

Three other profiles were taken of saprolites which had other economic uses: 1) In profile S-1, over the feldspar-rich pegmatite, the saprolite was used for the production of kaolin. In that profile, kaolinite was present in the clay fraction and in the larger size fractions as weathered feldspar grains. 2) In profile S-9, over pegmatite, saprolite was used mainly in the production of scrap mica. In that saprolite, muscovite was present as large grains, and only a small amount had been weathered to produce clay-size mica. Other products from that quarry were sand and clay. 3) Profile S-12, over Butler and Ragland's Concord Syenite, was obtained from a pit where the saprolite is mined for gravel.

Thus, weathering of the rocks in the study area has resulted in the formation of important residual clay deposits of various types which are of economic value.

SIGNIFICANCE OF HALLOYSITE

There has been some discrepancy in the literature as to the relative abundance or rarity of halloysite. Grim (1968) stated that "although the presence of halloysite in weathering products is well established, it is a rare component of such materials, and peculiar conditions must be required for its formation." However, halloysite has been reported by other workers, and Parham (1969b) lists references for 27 localities from aound the world where it has been identified.

The present study indicates that halloysite is a common constituent in the saprolites analyzed, sometimes making up as much as 90 percent of the < 2 µm clay fraction, and often in abundances of 20-30 percent of the clay fraction. In addition, halloysite was found not only in the saprolitized felsic rocks of the 12 profiles, but also in spot samples taken of saprolitized mafic rocks in the study area. This shows that halloysite forms from feldspars regardless of the rock type. As feldspars are abundant, halloysite is also abundant in weathering products.

Possibly, misidentification of halloysite in the past has led to the assumption that it is rare. The chemical compositions of kaolinite and halloysite are $Al_2Si_2O_5(OH)_4$, and $Al_2Si_2O_5(OH)_4 \cdot H_2O$, respectively, the only difference being the excess water in halloysite. This water is easily and irreversibly lost on dehydration, resulting in a collapse from a 10A to a 7A basal spacing. Thus, halloysite can be mistaken for kaolinite in samples that are not stored properly before X-ray-diffraction analysis.

The role of halloysite in the weathering of feldspars is not yet clearly understood. It is generally thought that kaolinite forms only as a secondary product of feldspar weathering. The primary products may vary depending on the weathering environment, and include halloysite, mica, or possibly allophane (Cady, 1950; Sand, 1956; Grant, 1962; Wolff, 1967; Gardner et al., 1978).

In the profiles studied here, halloysite has been the major product of feldspar weathering. Its common occurrence and local abundance suggest that it is probably quite common in other saprolites throughout the southeast. Halloysite is also found in other areas where weathering has taken place in tropical or subtropical climates. Parham (1969b) reports halloysite as an abundant weathering product of feldspar in young saprolite from Hong Kong. He suggests that halloysite is only preserved in young saprolite because it is altered to form kaolinite in more mature saprolite. The age of the saprolites in the present study is not known.

The presence of halloysite in the profiles from the study area is significant because it indicates that weathering took place in a humid environment, and that the environment of the weathering profiles has remained hydrous since the time of their formation.

CONCLUSIONS

The analysis of 12 saprolite profiles that formed over various crystalline rocks from the Charlotte 1° by 2° quadrangle in the Carolina Piedmont led to the following conclusions:

1) Most saprolite contained 10-25 percent clay, and the range was from 3-70 percent. Fluctuations in clay content within the profiles were found to be controlled by the changes in the mineralogy, grain size, and amount of feldspar weathering in the saprolite.

2) The similar clay-mineral assemblages over the various rocks studied indicate control of the clay mineralogy by the weathering process, rather than by the rock type. Abundant kaolinite and halloysite occur in the < 2 µm clay fractions of the saprolites.

3) Saprolite used for making building bricks had varied grain-size distributions, and the 2 m clays were predominantly kaolinite and clay-size mica with as much as 20 percent halloysite, and 5 percent mixed-layer mica-smectite.

4) The abundance of halloysite in the profiles indicates a continuously humid environment because halloysite quickly dehydrates irreversibly if not kept moist.

ACKNOWLEDGMENTS

The author thanks John Hosterman and Don Brobst for suggesting this study. Field support was given by Jesse Whitlow, John D'Agostino, and John Hosterman. Thanks also to Bob Luce and Milan Pavich for their helpful reviews of the manuscript.

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SOME PREDECESSORS OF *SOUTHEASTERN GEOLOGY*

By

James X. Corgan
Austin Peay State University
Clarksville, Tennessee 37040

ABSTRACT

The Virginias (1880-1885) and *The Southern Geologist* (1885-1886) were pre-professional experiments in regional geological communication. While they are now little used, students of southern geology should know all of the geological journals that have focused on the South.

INTRODUCTION

Readers of *Southeastern Geology* are familiar with the role a regionally oriented journal can play in disseminating geological information. *Southeastern Geology* is not the first journal that has attempted to serve the special needs of geologists who live and/or work in the southern states. This report briefly examines two journals that tried to serve the geological population of the South during the early and middle 1880's. The major reasons for discussing these ancient publications are to focus the attention of modern geologists on little-used intellectual resources and to call attention to inadequacies in contemporary knowledge of the history of the regional geological literature.

THE 1880'S

To discuss geological journals that were published a century ago, one must place them in a historical context. The population of geologists in the southern states in the early 1880's was very different from the modern population. In 1880, no federal agency maintained a geological staff in any southern state and no southern business used a salaried staff of professional geologists. In the 1880's, very few southern states had geological surveys with even a single full-time employee, and very few southern colleges offered more than one course in geology. In the early and middle 1800's, it was virtually impossible to make a living as a geologist in the South.

In the antebellum years, the southern states had pioneered in the development of the geological sciences (Corgan, In Press), but the years after the Civil War were far from a golden era in southern intellectual life. Then, in the 1880's, a few southern journals began to publish a significant number of geological studies.

To some extent, scientific journals are like snails and oreodonts, they have to live in adjustment with their environment and they change with the passage of time. The evolution of journals, and of snails, and of oreodonts is strongly influenced by space factors and by food factors. For journals, the critical space factor is library shelf space and the critical food factor is the consumption of manuscripts. In the South, during the 1880's, one new serial was created to see if available shelf space and manuscripts would permit the development of something called *The Southern Geologist*. Another new journal, called *The Virginias*, was designed as a business-oriented promotional device. While it was simply meant to foster regional industrialization, it soon consumed so many geological manuscripts that it became in fact, if not in philosophy, a regional geological journal.

In January, 1880, at Staunton, Virginia, Jedediah Hotchkiss published the first monthly issue of *The Virginias: A Mining, Industrial, and Scientific Journal Devoted to the Development of Virginia and West Virginia.* In December of 1885, the seventy-second monthly issue rolled off the press, and the journal ceased publication. Just what *The Virginias* was is debatable, in the same sense that one can debate whether the tree shrews should, or should not, be classified as primates. When *The Virginias* first appeared, there were few clear lines separating the various taxa of regional literature.

Jedediah Hotchkiss, who edited *The Virginias*, is a well known person (Thomas, 1976). He was a self-educated New York native who served as a topographer with Robert E. Lee, taught college, and worked as a mining engineer before establishing his journal. In the eyes of its editor, *The Virginias* was a propaganda device, designed to promote industrial investment by calling attention to the underdeveloped resources of Virginia and West Virginia. Most resources were either mineral resources or aspects of topography, like sites for water power development or ideal routes for railroads.

To carry its monthly load of editorial praise, *The Virginias* had to publish factual, objective reports that dealt with resources. There was no choice involved. *The Virginias* had to have geological reports to fill a monthly journal that was, in terms of its basic purpose, not a scientific journal. The first volume of *The Virginias* was dominated by geological articles, the longest of which was a serialization of an out-of-print classic (Currey, 1880). The last volume was also dominated by geology, including an original report on the activities of the fledgling U.S. Geological Survey (White, 1885). Volumes 2, 3, 4, and 5 were equally geological. There is no need to catalogue the impressive geological content of *The Virginias* because it has been competently indexed in the *Bibliography of North American Geology* (Nickles, 1924a; 1924b). Still, for purposes of the present brief article, it seems essential to characterize the geological content of *The Virginias* in general terms.

The geological content of *The Virginias* reflected the interests of the man who edited *The Virginias*. Reports were almost entirely descriptive. They stressed stratigraphy, regional geology, and individual mineral localities. As a topographer and mining engineer, the editor of *The Virginias* had been marginally involved in geological studies for several decades. While Hotchkiss disclaimed professional competence in geology, he was none-the-less unusually knowledgeable. He was personally acquainted with virtually every geologist who had ever worked in the Virginias and his personal library included virtually everything that had ever been published on the geology of the Virginias. Apparently, each original geological report that was published in The Virginias was solicited by Hotchkiss from an author he knew. Similarly, he personally selected out-of-print items for republication. Many original studies were prepared explicity for publication in *The Virginias*, since the prospect of publication was often enough encouragement to cause a geologist to study a topic he would not otherwise have studied.

Geological reports published in *The Virginias* not only reflect the fact that Jedediah Hotchkiss was interested in exploitable resources, they also reflect his expertise as a topographer and the fact that he was a lover of maps. In the 1800's very few journals published detailed topographic maps, multicolored geological maps, or complex geologic and topographic cross-sections. Such things were a specialty of *The Virginias*.

From the first issue through the seventy-second, geology so strongly dominated the pages of *The Virginias* that it has to be classified as a regional geological journal. Apparently, it was the first such publication in North America.

THE SOUTHERN GEOLOGIST

In October of 1885, just before *The Virginias* ceased publication, another geologically oriented southern journal appeared. *The Southern Geologist* is much less well known than *The Virginias*. At least three factors have lead to the relative obscurity of this Nashville-based publication. First, while *The Virginias* was indexed in the widely known *Bibliography of North American Geology*, the content of *The Southern*

Geologist has never been summarized in any indexed to the geological literature. To make up for this oversight, the total scientific content of known issues of *The Southern Geologist* is listed in an Appendix to the present article. Second, while *The Virginias* had a prominent editor who is now a well known historical figure, John A. Murkin, Jr., who edited *The Southern Geologist*, has never been the subject of a biography, and is an unknown person. Finally, while complete and partial sets of *The Virginias* are almost commonplace in modern libraries, no library has all known issues of *The Southern Geologist*.

To some significant extent, differences in present day knowledge of *The Virginias* and *The Southern Geologist* reflect the fact that they were geared to different audiences. *The Virginias* was sent free to institutions and to people of influence. Normally, *The Southern Geologist* just went to paid subscribers. Most subscribers were amateurs who collected rocks, minerals, and fossils. To reiterate, during the 1880's there were very few professional geologists in the South.

The editor of *The Southern Geologist* initially planned to call his publication *The Rock City Naturalist*. He circulated a prospectus, soliciting subscriptions, and several readers suggested the title that was finally used (Murkin, 1885). From the beginning, *The Southern Geologist* was geared to southern readers but was not restricted to southern topics, as is evidenced by the wide range of articles listed in the Appendix at the end of the present report. Murkin's journal also carried advertisements for collectables from all over the United States. For example, the first issue offered goods from dealers in Illinois, Kansas, Colorado, New York, Massachusetts, Florida, Missouri, Michigan, Indiana, and Dakota Territory. Mr. Murkin obviously had good connections and was probably an amateur himself.

Modern libraries contain six issue of *The Southern Geologist*. They appeared in October, November, and December of 1885 and in January, February, and April-May of 1886. Copies of a March issue were once preserved in both the Library of Congress and the State Library of Kansas, but neither copy can now be located.

In the February issue, an editorial announced plans to restrict the content so that the journal would "be devoted almost exclusively to the mineralogy of the South." At the same time, editor Murkin announced arrangements with agents who would sell his journal in Massachusetts, Colorado, and California. By the April-May number, an Iowa representative had been added. Clearly Murkin was trying to restructure both the content of his journal and its sales area. Apparently the reorganization did not lead to adequate sales and the journal expired.

SUMMARY AND CONCLUSIONS

Neither *The Virginias* nor *The Southern Geologist* has ever been discussed in a modern geological journal, yet both are important geological phenomena for they opened avenues of communication at a time when geological journals were a rarity. While no 19th Century serial exactly matches the 20th Century concept of a regional geological journal, both *The Virginias* and *The Southern Geologist* did many things that regional journals do today. In terms of service area and subject matter, they were predecessors of *Southeastern Geology*.

In the 1980's no one can speak confidently on a controversial topic in the geology of the southern states without first becoming familiar with the content of *Southeastern Geology*. Anyone who wants to gain a truly broad and general knowledge of southern geology needs to go beyond *Southeastern Geology* and thumb the pages of all the geological journals that have focused on the South.

ACKNOWLEDGMENTS

In the spring of 1979, George W. White, of the University of Illinois, and Allen F. Agnew, of the Library of Congress, read a preliminary version of this manuscript. It just dealt with *The Southern Geologist*. Costs of interlibrary loans and manuscript expenses were provided by an Austin Peay State University Tower Fund faculty research grant.

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APPENDIX

Content of *The Southern Geologist*

This appendix covers all known issues: volume 1, numbers 1, 2, 3, 4, 5, and 7. Copies can be obtained by interlibrary loan from Austin Peay State University, Clarksville, Tennessee 37040. No library now contains a copy of volume 1, number 6, which was issued in March of 1886.

This listing of the content of *The Southern Geologist* is restricted to articles. The journal also published scores of short filler items, often just two or three lines, as well as dozens of brief editorials and unsigned excerpts from newspapers, journals, and reference books.

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Alton, E.A., 1886b, Quarries: Southern Geologist, v. 1, no. 5, p. 5.

Alton, J.J., 1885, The Shrewsbury Mastodon: Southern Geologist, v. 1, no. 3, p. 2.

Anonymous, 1885a, Florida Fish Hawks: Southern Geologist, v. 1, no. 1, p. 3.

Anonymous, 1885b, Requirement to the Study of Nature: Southern Geologist, v. 1, no. 2, p. 6.

Anonymous, 1886a, Vanadanite and Descloizite: Southern Geologist, v. 1, no. 4, p. 1.

Anonymous, 1886b, The Middlesex Quarry: Southern Geologist, v. 1, no. 4, p. 5.

Anonymous, 1886c, Nashville and its Surroundings: Southern Geologist, v. 1, no. 5, p. 1-2.

Anonymous, 1886d, Determination of the Rock Forming Minerals: Southern Geologist, v. 1, no. 5, p. 2.

Anonymous, 1886e, (Milwaukee Well): Southern Geologist, v. 1, no. 5, p. 7.

Anonymous, 1886f, The Mound Builders: Southern Geologist, v. 1, no. 7, p. 3.

Clemens, William M., 1886, The Geology of Florida: Southern Geologist, v. 1, no. 7, p. 2-3.

Davis, J.L., 1885a, Iolite: Southern Geologist, v. 1, no. 1, p. 1.

Davis, J.L., 1885b, The Sandstone Quarries of Portland, Connecticut: Southern Geologist, v. 1, no. 3, p. 1.

Hibberd, S.L., 1886, Vermiculite at Mineral Hill, Pennsylvania: Southern Geologist, v. 1, no. 4, p. 2.

Lighton, W.R., 1886, A Day in Iowa Geology. Southern Geologist, v. 1, no. 7, p. 5-6.

Mann, Charles G., 1886a, Geological Formations of Central North Carolina: Southern Geologist, v. 1, no. 5, p. 3.

Mann, Charles G., 1886b, North Carolina: Southern Geologist, v. 1, no. 7, p. 1.

Moorehead, Warren K., 1885, Mounds and Relics of Greene County, Ohio: Southern Geologist, v. 1, no. 2, p. 3.

Murkin, John A., Jr., 1885, Special Notice: Southern Geologist, v. 1, no. 1, p. 5.

Newcomb, C.F., 1885, Indian Mounds: Southern Geologist, v. 1, no. 3, p. 3.
Phillips, J. Van Cleve, 1886, Minerals and Patriotism: Southern Geologist, v. 1, no. 4, p. 2.
Stilwell, L.W., 1885a, Uranite: Southern Geologist, v. 1, no. 1, p. 2.
Stilwell, L.W., 1885b, Dendrites: Southern Geologist, v. 1, no. 3, p. 2.
Stilwell, L.W., 1886, "Bad Lands" Fossils: Southern Geologist, v. 1, no. 5, p. 3.
Stuart, Henry, 1885, Mineral Wealth of Western North Carolina: Southern Geologist, v. 1, no. 2, p. 1.
Wells, G.E., 1886, Indian Relics in Montgomery County, New York: Southern Geologist, v. 1, no. 4, p. 3.

SOME OBSERVATIONS ON SLOPE DEPOSITS IN THE VICINITY OF GRANDFATHER MOUNTAIN, NORTH CAROLINA

By

Hugh H. Mills
Department of Earth Sciences
Tennessee Technological University
Cookeville, Tennessee 38501

ABSTRACT

Extensive sheets of bouldery colluvium cover the slopes in the vicinity of Grandfather Mountain. Although the slopes are smooth in their gross aspects, in detail they are dissected by numerous shallow drainageways, ephemeral for the most part. Road cuts show that colluvium in and near these drainageways is only slightly weathered, suggesting a relatively young age, whereas colluvium on low interfluves between the drainageways generally is weathered substantially, suggesting a somewhat greater age. Two topographic profiles surveyed across slope parallel to road cuts showed that these relationships hold even when drainageways are only a few meters wide, interfluves a few tens of meters wide, and cross-slope relief a few meters. They also showed that boulder deposits on the lower slopes are confined mainly to drainageways. At some locations younger colluvium overlies older. Logs from 13 wells on the northwest flank of Grandfather Mountain reveal a mean depth to bedrock of 16.7 m, although this figure includes saprolite as well as colluvium.

Relative dating of deposits was attempted by measuring percent clay, color, and percent weathered clasts. Although percent clay showed no consistent variation, hue and percent weathered clasts successfully distinguished the younger and older colluvium and suggested that there may be a time hiatus between the two. Such a hiatus suggests, although it does not prove, a climatic control of colluviation. This observation and the large volume of colluvium on the slopes suggest former periglacial conditions, but no truly distinctive features indicative of such conditions were seen. All observed features of slope deposits probably could have been produced by catastrophic floods and other processes associated with the present climatic regime. Hence, although pollen evidence from the central and southern Appalachians makes it likely that periglacial conditions did exist on Grandfather Mountain during the late Wisconsin, and although the slope deposits are compatible with a periglacial origin, such deposits do not constitute independent evidence of a periglacial environment.

INTRODUCTION

Grandfather Mountain has been the scene of controversy over the existence of Pleistocene alpine glaciation in the southern Appalachians. Although Berkland and Raymond (1973) and Raymond (1976, 1979) have argued for such glaciation, many of their arguments have been vigorously attacked by Hack and Newell (1974), McKeon (1974), and Carson and others (1974). Perhaps less controversially, Raymond (1976) has claimed evidence of Pleistocene periglacial action on this mountain. The present paper describes some observations made on the slope deposits of Grandfather Mountain and nearby mountains during the summer of 1977, and evaluates their implications for slope processes and Pleistocene climates.

GEOLOGIC SETTING

The study area (Fig. 1) is located within the Grandfather Mountain window in the Blue Ridge thrust sheet in western North Carolina, and is underlain by rocks of the

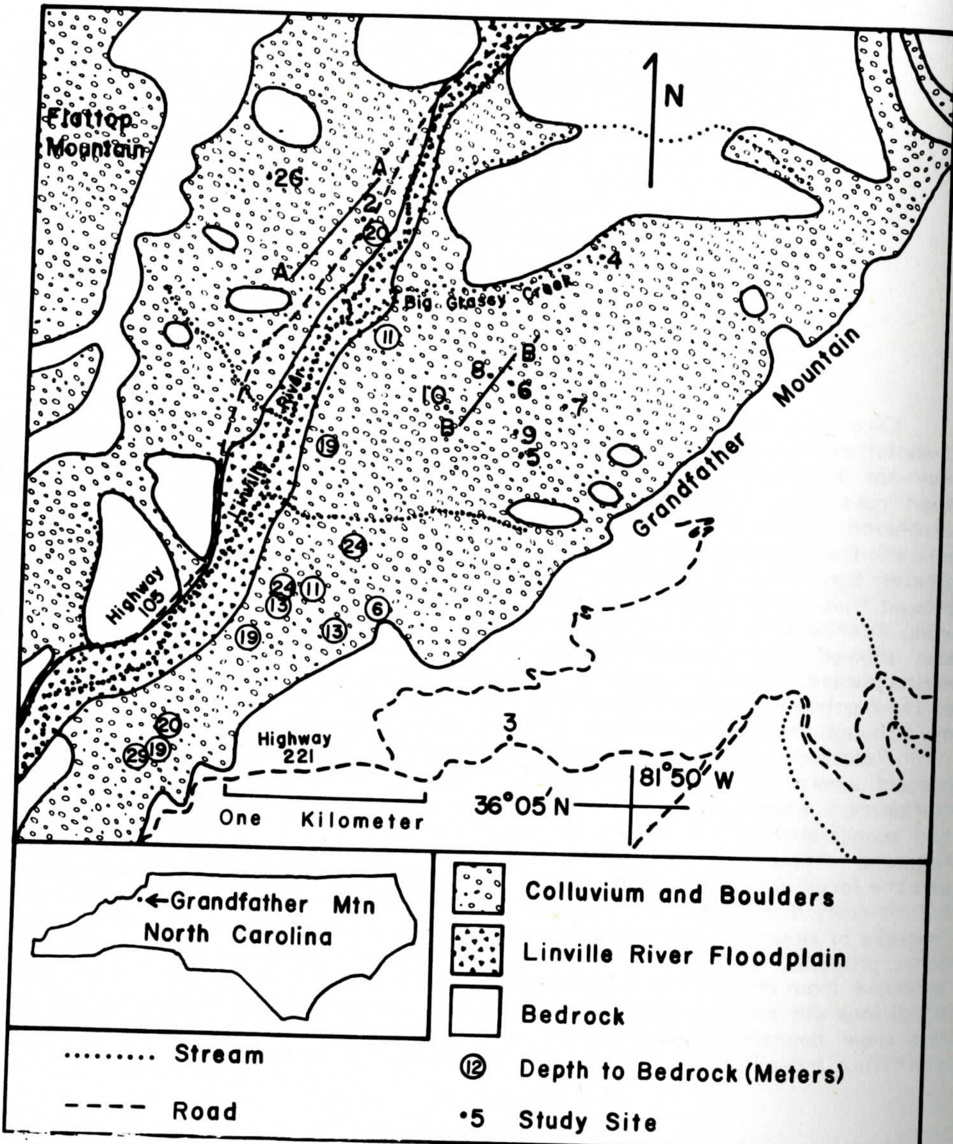


Figure 1. Overlay map of study area, showing extent of colluvial deposits, study sites, and depths to bedrock at drill holes (map after Bryant and Reed, 1970, Plate 1). The study area is located on the Grandfather Mountain quadrangle in Avery County, North Carolina. The lines A - A′ and B - B′ are the locations of topographic profiles surveyed near sites 2 and 8, respectively. Site 1 is located to the north of the map area.

mildly metamorphosed late Precambrian Grandfather Mountain Formation. According to Bryant and Reed's (1970) map, arkose and subarkose made up about 50% of this formation, siltstone about 35%, and metamorphosed volcanic rocks the remaining 15%. The arkose units contain beds and lenses of conglomerate, the clasts of which are mostly in the small cobble to coarse pebble range (Schwab, 1977), although occasionally they are somewhat larger. The clasts in the conglomerate consist of quartz, feldspar, granite, gneiss, volcanic rock, sandstone, and siltstone (Schwab, 1977). Commonly arkose forms the cliffs and slabby outcrops in the area, whereas the siltstones underlie the valleys and footslopes.

The soils map of the Linville quadrangle (Goldston and others, 1955) shows a relatively small number of soil series in the study area. The upper slopes are characterized by Ramsey series or by what is classified simply as "Stony rough land," except that the top of Flattop Mountain is covered with Matney series. The middle slopes are covered with Matney series, and the footslopes with Tate series. The Ramsey series is classified as a lithosol (probably an inceptisol under the new classification), the Matney as a gray-brown podzolic soil (probably equivalent to an udalf or udult), and the Tate series as a red-yellow podzolic soil (probably equivalent to a udult). Hence, as the B2 horizons of the red-yellow podzolic soils seem to be better developed than those of the gray-brown podzolic soils, the soils appear to be better developed and therefore probably older farther down the slope. It should be pointed out that the soils mapping was done in only a very general fashion, as is usually the case in mountainous areas with little agricultural potential.

PREVIOUS WORK

Most of the information on surficial sediments in the southern Blue Ridge province has been provided by geologists primarily engaged in bedrock mapping. A thin (1 m or so) layer of colluvium has been observed to be a nearby ubiquitous feature in this region. More interesting are relatively thick colluvial deposits which occur more selectively. Many such deposits occur as fan-shaped features in piedmont coves, where they grade into alluvium at their distal ends. Such features have been described in the Great Smoky Mountain region by Hamilton (1961), Hadley and Goldsmith (1963), and King (1964), and in Wautauga County by Gryta and Bartholomew (1977). The most comprehensive study, however, was by Michalek (1968), who studied the distribution and other properties of these features throughout the southern Blue Ridge province.

Many authors have inferred that these features were formed by periglacial action during the Pleistocene. As evidence, Michalek (1968) cited the fact that the fans currently appear to be undergoing erosion rather than deposition, that the upper ends of many fans are covered by block fields, that no fans are found below about 700 m, and that fans diminish in both number and development southward, becoming uncommon south of Asheville, North Carolina.

Hack and Goodlett (1960) and Gryta and Bartholomew (1977), however, have argued that processes not associated with colder climates might form such features. They have suggested that such fans may be formed by debris flows set off by rare, catastrophic rainstorms. Dramatic support for this hypothesis was provided in August, 1969, when Hurricane Camille dumped up to 710 mm of rain in 8 hours on parts of central Virginia, setting off hundreds of debris flows which covered some fan surfaces in that area with bouldery debris up to 60 cm in mean depth (Williams and Guy, 1973). These deposits were very similar to colluvium and contained blocks up to 2 m in diameter. Even though such a rainfall probably has a recurrence interval on the order of 1000 years (Thompson, 1969), one can visualize a sequence of storms building up sizeable fans within several tens of thousands of years.
Similar but smaller phenomena associated with other storms have been reported by Moneymaker (1939) and Bogucki (1970, 1976). Although this explanation does not explain the altitudinal and latitudinal distribution of fans described above by Michalek (1968), it certainly could account for some of the fans, and therefore must be considered as an alternative to the periglacial hypothesis, at least locally.

Although no absolute ages have been obtained for any colluvial deposits, many investigators have reported multiple ages of such deposits in this region (Hadley and Goldsmith, 1963; King, 1964; Michalek, 1968; Gryta and Bartholomew, 1977; and Mills, 1977). The age differences are indicated by differences in degree of weathering and by topographic relationships. Whether such age variation indicates episodic deposition, and in particular episodic deposition produced by alternation of glacial and non-glacial climates, remains uncertain.

Colluvial deposits may in part be derived from the erosion of saprolite, which is extensive throughout the Blue Ridge. Reed (1964) noted that in the Linville Falls (1:62,500) quadrangle (which includes the study area), saprolite is present even in the most mountainous areas. King (1964) and Hadley and Goldsmith (1963), however, noted that saprolite was poorly preserved at higher altitudes in the Great Smoky Mountains.

They noted that the lower part of saprolite commonly is yellow or yellowish orange, whereas the upper part is red. In higher locations the upper red part was absent, indicating that it had been removed by erosion.

Accumulations of large boulders, often called block fields or block streams, are common on Grandfather Mountain and elsewhere in the southern Appalachians wherever resistant bedrock and steep topography occur. Such accumulations have been described by Hamilton (1961), Hadley and Goldsmith (1963), King (1964), Hack (1965), Michalek (1968), Haselton (1973), Godfrey (1975), Hedges (1975), and Raymond (1976). Most authors have cited these features as evidence of former periglacial conditions. Although certainly suggestive, however, block fields and streams are by no means definite proof of such conditions. Hack (1960, 1965), for example, cited evidence of present-day scree production and has suggested that scree develops wherever slopes are steep and the bedrock is mechanically strong and resistant to chemical weathering, regardless of climate. In addition, debris flows resulting from catastrophic rainfalls could move boulders of virtually any size downslope. Even boulder deposits lacking a matrix may have been emplaced in this manner, as it is likely that many such deposits lose their matrix by post-depositional eluviation of fines (e.g., White, 1976, p. 93; Washburn, 1980, p. 221).

PROCEDURE

Roadcuts on the lower slopes of Grandfather Mountain and nearby mountains were examined. Exposures provided by roads recently constructed by the GF Company on the northwest flank of Grandfather Mountain were particularly instructive. At 10 sites (several having multiple subsites) descriptions and measurements were made. A total of 28 fine samples were collected; the texture and color (Munsell, moist condition) of these were determined in the laboratory.

Because the colluvium at many sites contains a large proportion of cobbles and boulders, analysis of the fine samples alone is inadequate. An accurace description of the particle-size distribution of the entire clast-size range, however, would require laborious field-sieving of large samples. As time was not available for such a procedure, an alternative technique was used to gain some impression of the texture of the coarse fraction. At six relatively fresh cuts, a tape was stretched across the exposure and the size of clasts beneath the tape measured at regular intervals. This technique was unsatisfactory for smaller clasts, and so clasts less than 8 mm in intermediate diameter were lumped together into a "less-than-8-mm" category.

Clast weathering was measured as follows. At 29 locations, 25 clasts approximately in the pebble size range were randomly selected from the exposure and classifed into one of several weathering classes. For purposes of this paper these categories have been reduced to two, the dichotomy based on whether or not the clasts could be broken apart by hand (into pieces the size of granules or smaller). At 7 locations having predominantly unweathered clasts, pebble roundness was measured for 25 pebbles (between 16 and 32 mm in intermediate diameter) using the visual comparison chart of Krumbein (1941).

It was desirable to show the relationship between small-scale topography and the distribution of surface boulders, particularly in a cross-slope direction. This was accomplished as follows. A line was hand-levelled along an azimuth approximately parallel to the generalized slope contours, and the diameter of the surface clasts measured at 3 m intervals. One problem encountered was that boulders were frequently obscured by a thin organic mat; recording "no clast" for such locations obviously would be inaccurate. Therefore, where no clast was visible on the surface, a 10-cm-long rod was inserted into the ground at that point, and any clast encountered by this rod was dug out and measured. If no clast was encountered within 10 cm of the surface, or if a clast less than 8 mm in diameter was encountered, a "less-than-8-mm" measurement was recorded. This procedure was carried out at two sites where the survey line was parallel to and slightly uphill from roads. The road cuts allowed the subsurface conditions to be determined, thus allowing the association between topography, surface sediments, and subsurface sediments to be ascertained.

Numerous wells have been drilled on the GF Company property for homesites.

Logs from 13 of these wells were obtained from Mr. Hugh Braswell, driller, of Newland, North Carolina. Unfortunately the logs indicate only the depth at which unweathered bedrock was encountered, not distinguishing between saprolite and the overlying colluvium.

RESULTS

General Results

Figure 1 shows much of the northwest slope of Grandfather Mountain and the southeast slope of Flattop Mountain to be mantled with colluvium. Unlike the fan-shaped deposits discussed above, these deposits have a sheet- or apron-like form. They have a concave-upward slope, decreasing in angle from about 20° near the crest to as low as 5° near the Linville River. Although the slopes are smooth in their gross aspects, in detail they are dissected by numerous shallow drainageways, ephemeral for the most part.

Depth to bedrock of drill holes are shown in Figure 1. The mean depth of the 13 holes is 16.7 m, with a range of 6.1 m to 29.3 m. Hence the mean thickness of colluvium is probably on the order of 10 m, recalling that part of the measured depth is in saprolite. Although much thicker than ordinary colluvial deposits, this is perhaps less thick than one might expect from the great areal extent of the deposit.

The colluvium was divided into two age groups according to its topographic position. Colluvium in or near the modern drainageways usually showed little evidence of weathering; this will be referred to as "young" colluvium. Usually its surface was bouldery. On the interfluves between the drainageways, however, the colluvium showed evidence of weathering and had a much lower surface-boulder density. This will be referred to as "old" colluvium. In some cases colluvium with weathering characteristics similar to those of "young" colluvium was seen overlying "old" colluvium. This also was classified as "young," although in some cases it was not near modern drainageways.

Figure 2 shows the percent sand, silt, and clay of each sample on a truncated ternary diagram. Most of the samples fall into the loam, clay loam, or sandy clay loam classifications. The open circles are young samples, whereas the solid circles are old ones. The diagram shows no apparent textural differences between the two groups of samples. The textures of the coarse fraction will be discused with the descriptions of individual sites.

Three properties were used as weathering indices for the deposits: hue (as

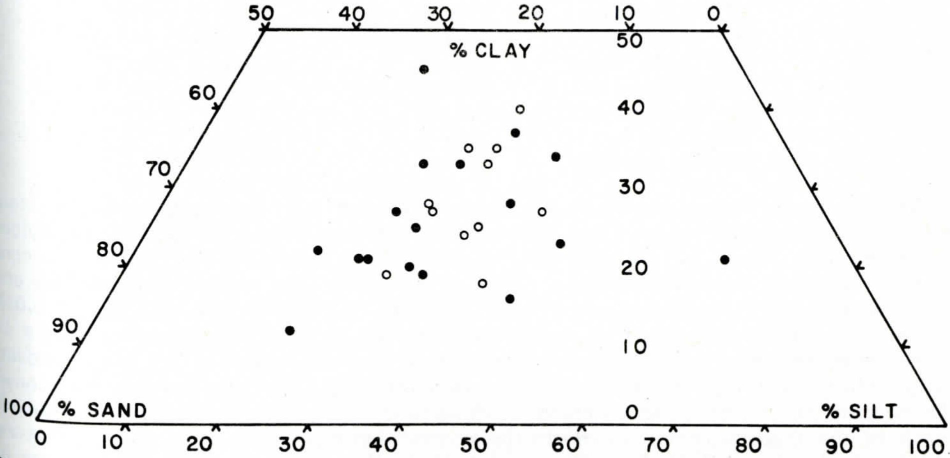


Figure 2. Truncated ternary diagram showing percent sand, silt, and clay (scale of Wentworth, 1922) in the less-than-2-mm fractions of colluvial samples. Open circles represent samples of younger colluvium, solid circles represent samples of older colluvium.

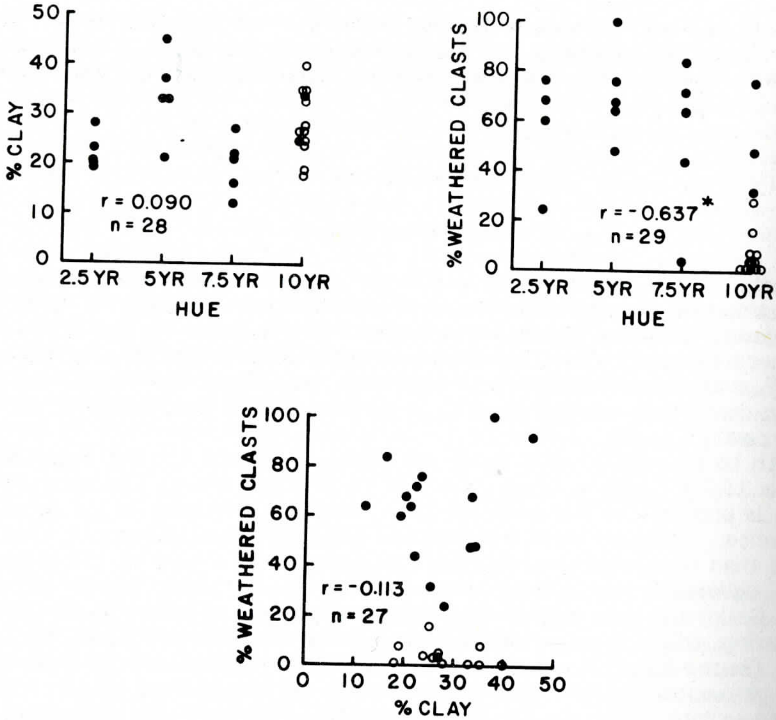


Figure 3. Interrelationships between the weathering indices percent clay, hue (Munsell notation, where 2.5 YR is most red and 10 YR least red), and percent weathered clasts. Asterisk indicates $p \leq 0.01$. Open circles represent samples of younger colluvium, solid circles represent samples of older.

Table 1. Pebble-Roundness Measurements

Site No. and Character	Distance from Crest	Mean Roundness
1B Colluvium	800 m	1.28
2C Colluvium	1300 m	1.36
3 Colluvium	480 m	1.60
4A1 Colluvium	1400 m	1.56
4A3 Colluvium	1400 m	1.80
4B Colluvium	1400 m	2.00
4A2 Modern Stream Gravel	1400 m	3.12

determined from a Munsell color chart), percent clay in the less-than-2-mm fraction, and percent weathered clasts. In Figure 3 the interrelationships of the three indices are examined by means of x - y plots for each of the three possible pairs. Percent clay shows virtually no relationship to either of the other two indices, whereas hue and percent weathered clasts show a significant inverse correlation ($r = -0.637$, $p \leq 0.01$). Note that this correlation owes its existence primarily to the fact that sites with a 10 YR hue generally have few weathered clasts. For sites with hues of 7.5 YR or redder, however, there is little relation between the two variables. That the percent clay shows little relation to degree of weathering as defined by the other two indices probably is a result of the disaggregation of clasts during weathering. As sandstone and siltstone clasts break down and contribute their component grains to the matrix, the percent of clay in the matrix may actually decrease. Over 90% of the clasts used for the weathering clasts were arkose, with most of the remainder being siltstone. Volcanic clasts were rare.

One of the purposes of measuring the weathering indices at a number of sites was to determine whether colluvial deposits could be divided into discrete groups on this basis. In Figure 3, open circles again represent young sites and solid circles, old. The plot of percent weathered clasts against hue suggests that the young colluvium can be fairly sharply distinguished from old. Young colluvium almost always has 10 YR hues and less than 10% weathered clasts. Of 12 young samples, all had 10 YR hues, 10 had 8% or fewer weathered clasts, one had 16%, and one had 28%. In contrast, of the 17 old samples, all but 3 were redder than 10 YR and all but 3 had 48% or more weathered clasts. Within the latter group, however, there appears to be no grouping, but rather a continuum from least to most weathered. Scatter within the old colluvium decreases if only the most weathered sample at each site is considered. However, even when this is done there is no apparent grouping.

Pebble roundness results are shown in Table 1. Note that the mean roundness values for colluvial samples is somewhat lower than that for a sample from the channel of Big Grassy Creek. Comparison with a compilation of stream-pebble roundness data from a number of authors (Mills, 1979, Fig. 1) shows that the 3.12 value from Big Grassy Creek is about average for a maximum travel distance of 1400 m. The values for the colluvial samples, however, for the most part are somewhat lower than those reported for stream pebbles. This result supports the generally held opinion that colluvium contains angular clasts.

Descriptions of Individual Sites

Site 1 (not shown on Fig. 1) is about 2.9 km northeast of Linville Gap on Highway 105 (Valle Crucis quadrangle), and consists of a cut through a colluvial apron on the southeast side of Peak Mountain. The elevation is 1110 m. This exposure is particularly interesting because it reveals what appear to be several superimposed units. Although the road cut is too obscured to make any interpretations with confidence, the situation seems to be that of a channel cut into older deposits which has been filled and then covered with several meters of younger material. A narrow section down the exposure was cleared of slopewash debris and described. Four units were distinguished on the basis of color changes and manganese-oxide bands.

All units were classified as old, as the deposit lies well above nearby drainageways. It appears, however, that the upper unit is substantially younger than the lower ones, as indicated by a less-red hue and a lower percentage of weathered clasts. The upper unit and two of the lower ones show evidence of greater weathering in their upper parts than in their lower parts, perhaps suggesting buried soil profiles in the case

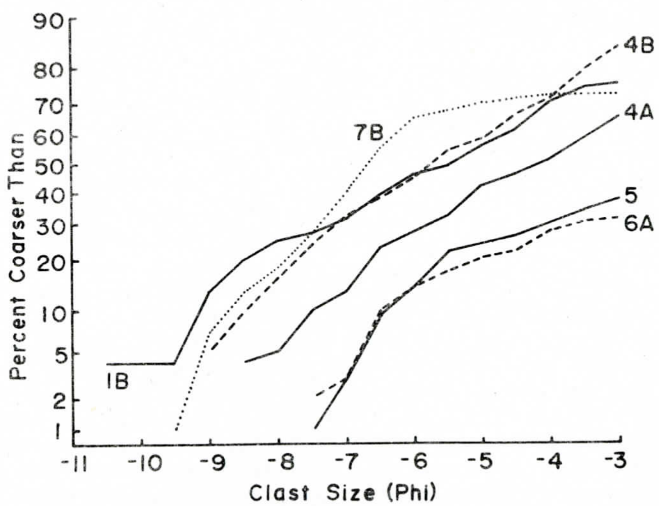


Figure 4. Cumulative particle-size distributions of coarse fraction of colluvium ($\geq$ 8 mm) as determined from point counting on road cuts using grid.

of the two lower ones. The manganese-oxide bands appear to have been deposited by percolating groundwater along contacts between units. However, as all contacts except the one between the lowest two units are indistinct, the possibility exists that the concentrated groundwater flow that produced the manganese-oxide bands also produced the apparent weathering profiles, and therefore that the three lower units do not really represent three distinct depositional events.

Figure 4, curve 1 B, shows the results of a point count of the greater-than-8-mm fraction of the upper unit. The size distribution is roughly normal with a median clast size of -5.4 ϕ (42 mm).

Site 2 (Fig. 1) is located on the southeast side of Flattop Mountain about 1.4 km southwest of Linville Gap on Highway 105. The elevation is about 1207 m. The road cuts in this vicinity nicely demonstrate that the drainageways on the lower slopes are underlain by relatively unweathered colluvium and the intervening interfluves by moderately to highly weathered colluvium. To demonstrate this relationship, a cross-slope line over 600 m long was surveyed parallel to the road, as discussed in the procedures section. On the profile (Fig. 5a), R indicates red (and therefore older) soils, whereas B indicates brown (and therefore younger) soils as revealed by the road cuts downhill from the profile. Note that the drainageways have large numbers of boulders on their floors, whereas the interfluves have relatively few. Exceptions appear to occur on the broad interfluve between about 300 m and 500 m along the profile. Closer inspection, however, reveals reasonable explanations for these apparent exceptions. Note that the concentrations at 450 m and 490 m actually are related to slight swales which are minor drainageways. The apparent exception at 320 m has a different explanation. A badly slumped road cut reveals what appears to be a channel in the old colluvium filled with young bouldery colluvium (hence the B at 320 m in Fig. 5a).

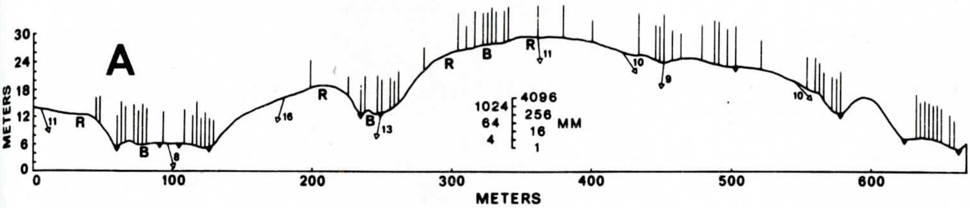
Seven subsites were located in this vicinity. The reddest hues at the old sites were 2.5 YR, 2.5 YR, and 7.5 YR, whereas the four young sites they were all 10 YR. The percent weathered clasts was 76, 68, and 72 at the old sites, and 0, 0, 0, and 8 at the young. Site 2 G (Fig. 1) was located farther up the slope at an elevation of 1302 m, with a slope of 8^{o}. Although on an interfluve, a 1-m deep pit revealed only young colluvium, which together with the fact that the surface was somewhat more bouldery than that of interfluves farther down the slope, suggests that locations where older, more weathered colluvium occurs near the surface are confined to the lower slopes.

Site 3 is located about 0.5 km east of the Grandfather Mountain entrance gate on Highway 221 at an elevation of 1302 m. The slope is 20^{o}. Note that no colluvium is mapped at this site on Figure 1, for this is an area of thin, discontinuous colluvium. Site 3, then, is an example of "ordinary" colluvium on relatively steep slopes. The colluvium showed little weathering, having a hue of 10 YR and only 4% weathered clasts; it was therefore classified as young. It is about 1.2 m thick and overlies saprolitized arkose.

Sites 4 - 10 are located on the northwest slope of Grandfather Mountain along roads recently constructed by the GF Company. Site 4 is located near Big Grassy Creek at an elevation of 1305 m (Fig. 1). The slope is about 12^{o}. Here two levels of colluvium occur adjacent to the creek. Although the higher one appears to be slightly more weathered, both have 10 YR hues and few weathered clasts. Grids for both are shown in Figure 4. The median size for the upper level (4 A) is -4.2 ϕ (18 mm) and for the lower level (4 B) is -5.7 ϕ (52 mm). Both subsites were classified as young.

Site 5 is at the end of Wildflower road at an elevation of 1280 m. The surface slope is 5^{o}. There appears to be a slightly weathered layer of colluvium about 1.0 m thick overlying a thicker, more weathered unit, although the contact between them is gradual. Although the color difference between them was slight (10 YR vs. 7.5 YR), the upper layer had only 8% weathered clasts, whereas the lower layer had 76%. A reddish (5 YR 5/8) clay-rich (49% clay) lens about 4 m long was observed in the lower unit, perhaps indicating part of a paleosol incorporated during colluviation. The upper unit was classified young, the lower, old. Both layers were rather fine grained. A grid (Fig. 4, curve 5) showed the upper layer to have 63% of its clasts less than -3 ϕ (8 mm) in diameter, so that it can be stated only that the median size is less than that.

Site 6, near the green of hole 12 on the golf course, has a slope of 9^{o} and an



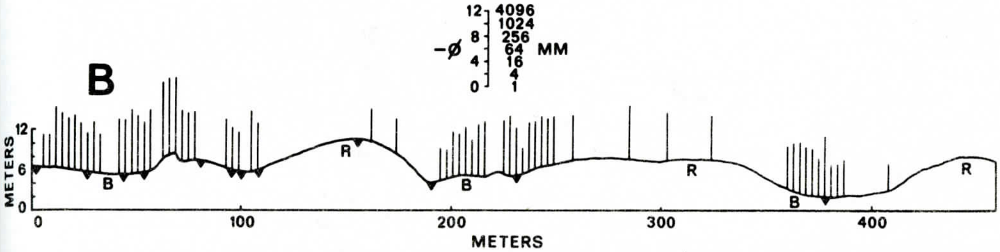


Figure 5. A. Topographic profile surveyed along line A - A' on Figure 1. View is uphill. Length of vertical line indicates intermediate diameter of clast measured at that point on profile. Absence of line indicates clast at that point was less than 8 mm. Inverted solid triangles indicate drainage channels, mostly ephemeral in nature. R indicates reddish soil and B brownish soil exposed in road cut downhill from profile. Arrows indicate actual direction of slope at given points, where an arrow pointing directly toward the bottom of the page indicates a slope direction at right angles to the profile line, and arrows deviating from this direction show the degree to which local slope directions deviate from a slope at right angles to the profile. Numbers by the arrows indicate slope angles. B. Topographic profile surveyed along line B - B' on Figure 1. View is uphill. Length of vertical line indicates intermediate diameter of clast measured at that point on profile. Absence of line indicates clast at that point was less than 8 mm. Inverted solid triangles indicate drainage channels, mostly ephemeral in nature. R indicates reddish soil and B brownish soil exposed in road cut downhill from profile.

elevation of 1274 m. Site 6 A is a very fine-grained, slightly weathered colluvium (hue 10 YR, 16% weathered clasts) that was classified as young. A grid of this site (Fig. 4, curve 6 AW) produces a curve similar to that of site 5, with 60% of the clasts less than -3 ϕ (8 mm) in diameter. On a rise 40 m south of 6 A is site 6 B. This old colluvium has a hue of 2.5 YR and 76% weathered clasts.

Site 7 A, a road cut between hole 9 and 10, has a slope of 16^{o} and an elevation of 1311 m. A hue of 10 YR and 4% weathered clasts indicate a young age. Nearby the road cuts through what appears to be the deposits of a small ephemeral stream. Although poorly sorted, the fluvial influence on these sediments is suggested by the relatively small amount of matrix. A grid of this site (Fig. 4, curve 7 B) shows this deposit to be the coarsest measured, having a median size of -6.7 ϕ (104 mm). Site 7 C, with a slope of 12^{o}, is about 20 m southwest of the southwest end of hole 9. A cut here reveals older material, with a hue of 5 YR and 68% weathered clasts.

Site 8 is located along Bridle Trail Road just downhill from hole 12. The elevation is 1256 m and the slope is about 9^{o}. Site 8 A is located about 40 m south of a large stream channel and consists of young colluvium (hue 10 YR, 0% weathered clasts). Site 8 B is 20 m north of the same stream channel and consists of old colluvium on a small interfluve. The hue was 5 YR and the clasts were too scarce to obtain a clast-weathering sample, although the few clasts seen were highly weathered.

A topographic profile about 450 m long was surveyed near this site, parallel to and uphill from Bridle Trail Road, between its intersections with Buckeye Road and Wildflower Road (Fig. 5b). This profile reveals an even better relationship between topography and colluvial properties than did site 2. Despite the fact that the cross-slope relief is only a few meters, the boulders are almost entirely restricted to the drainageways (the apparent interfluve at about 70 m actually is an enormous boulder). In addition, as was the case for site 2, the younger brown soils are associated with the drainageways and the older red soils with the noses (Fig. 5b). The downhill slope along the profile ranges from 8° to 10°.

One difficulty with this topographic profile is that it is not absolutely certain that the weathered material on the interfluves is colluvium. It is so devoid of stones that it conceivably could be *in situ* siltstone residuum, although no stratification or other relic bedrock structures were evident. (There is much less difficulty in distinguishing weathered stony colluvium from saprolitized Grandfather Mountain conglomerate, for the latter, besides being more uniform in clast size, has clasts that are much more highly rounded than those in the colluvium. In addition, the saprolite contains many igneous clasts easily recognized even when weathered, whereas the clasts in the colluvium are mainly arkose.) Site 9 is an exposure of moderately weathered colluvium (hue 10 YR, 52% weathered clasts, classified old) near the top of Wildflower road at an elevation of 1287m. Site 10 is a slightly weathered colluvium (hue 10 YR, 28% weathered clasts, classified young) exposed in a creek at about 1238 m. It occurs on Bridle Trail Road about 0.15 km above the intersection of this road and Mountain Springs Road.

DISCUSSION

No organic remains were found in the colluvium. Hence, the best that can be done with regard to absolute dating is to make order-of-magnitude comparisons with glacial deposits of known age in the northeastern and midwestern United States on the basis of weathering characteristics and soil profiles. On this basis, my impression is that the younger colluvium could be Holocene or late Wisconsin in age, but is unlikely to be older. The older deposits, which range greatly in their degree of weathering, probably range from mid-Wisconsin to pre-Illinoian in age. The bulk of the colluvium probably is no older than Wisconsin in age, as highly weathered colluvium is relatively uncommon.

The use of hue as a weathering index is based upon the assumption that the iron oxide in the older colluvium is derived from post-depositional weathering. King (1964), however, thought that the red color of older colluvium in the Great Smoky Mountains might result from the fact that older colluvium was derived from the red, upper part of the saprolite, whereas the yellow or brown color of the younger colluvium results from its derivation from the yellow basal part of the saprolite. Richard Goldsmith (written communication, 1977), however, concluded that appreciable weathering (and thus presumably production of the red color) had occurred *in situ*. I concur with Goldsmith, my reasoning being as follows. The colluvial deposits with hues redder than 10 YR almost always contain a high percentage of weathered clasts. The latter must have weathered *in situ*, for transport after weathering would have destroyed them. It seems reasonably to suppose that weathering sufficiently intense to weather the clasts would also be sufficient to increase the iron-oxide content of the soil substantially.

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Some check on the above age approximations can be obtained by a consideration of the thickness of the colluvium in light of probable erosion rates. Hack (1979) compiled estimates from a variety of sources and concludedthat an erosion rate on the order of 40 mm/1000 yr has prevailed over geologic time in the Appalachian region. However, erosion rates are usually somewhat greater in small, steep drainage basins than they are when averaged over wide regions, because in the latter case lowland areas with low erosion rates are included. Young (1969) compiled data from many studies and concluded that erosion rates in areas of steep relief range from about 100 to 1000 mm/1000 yr. As Grandfather Mountain is comprised of quite resistant rock and lacks the relief and extensive steep slopes of alpine mountains, a figure of 100 mm/1000 yr seems about the correct order of magnitude for erosion here.

The mean depth to bedrock is about 16.7 m. Let us assume that 10 m of that is colluvium, the remainder, saprolite. The density of colluvium is about two thirds that of bedrock, so that 10 m of colluvium is equivalent to 6.667 m of bedrock. To erode this thickness of bedrock, assuming an erosion rate of 100 mm/1000 yr, would require only 66,670 yr. Of course part of the eroded material would have been carried off the slopes into the Linville River, which would increase the time required to accumulate the observed thickness of colluvium, but on the other hand some of the colluvium undoubtedly was derived from saprolite, which could be eroded somewhat more rapidly than could bedrock. In addition, of course, erosion rates probably were somewhat higher than average during full-glacial climates. Thus, these considerations support the concept that much of the colluvium is no older than Wisconsin in age.

One question that arises concerning the source of the colluvium is what proportion of boulders on the northwest flank of Grandfather Mountain was derived from the cliffs near the crest of the mountain. It seems probable that this proportion was a small one, for Flattop Mountain has virtually no cliffs on its southeast side, yet boulders seem to be as plentiful on its slopes as they are on those of Grandfather Mountain.

As stated in the section on previous work, many authors have inferred former periglacial conditions from features such as I have described on Grandfather Mountain. Pollen records suggest that the climate in the central and sothern Appalachians was much colder during the last glacial maximum (e.g., Watts, 1975, 1979), and as the present mean annual temperature at an elevation of 1463 m on Grandfather Mountain is only 8.3^{o} C, a former periglacial environment appears quite probable. Nevertheless, the question remains of whether or not features occur on the mountain that could have formed only under a climatic regime much more severe than that now prevailing. The answer appears to be no. Raymond (1976) cites as evidence of periglacialconditions the existence of "till-like" deposits, tors, blockfields, blockstreams, carpedoliths, and a possible solifluction lobe. None of these however, are unique to periglacial environments. Washburn (1980, p. 282-283) lists a number of features which may be indicative of periglacial action, such as patterned ground and involutions, but none of these were observed on Grandfather Mountain. Benedict (1976) lists nine characteristics of gelifluction, but many of these are also found in other types of mass-wasting deposits, and the more distinctive ones were not seen in the Grandfather Mountain colluvial deposits.

It is of some interest to note that redder (and therefore presumably older) soils appear to occur only on the lower slopes of the mountain. This might suggest a climatic control, in that on higher slopes such soils might have been eroded away by more intensive frost action, or they might have been buried beneath younger colluvium which was produced in greater quantities on the upper slopes than on the lower. However, it also may be simply that the greater slope angle found on the upper slopes is responsible for this difference.

Probably the characteristic most suggestive of periglacial conditions is simply the fact that the colluvial and boulder deposits occur in such large quantities on the mountain slopes. This, of course, is far from definitive proof of such conditions. One other suggestive finding is that the weathering indices of the colluvium do seem to indicate a time gap between the young colluvium and the older deposits, which might imply episodic deposition due to climatic control. True, catastrophic flooding would also result in episodic deposition, but if the recurrence interval of such floods is really on the order of 1000 years (Thompson, 1969), it seems unlikely that intervals between depositional episodes would be sufficiently long to allow distinct weathering differences to develop between successive deposits. Such evidence is, of course, very tenuous.

Although evidence of periglacial conditions is scanty, there is no evidence to disprove the periglacial hypothesis, either. The fact that on the lower slopes boulders and young colluvium occur mainly in association with the modern drainageways is compatible with the transport of such deposits by catastrophic floods, but it is by no means incompatible with transport by gelifluction, for moisture is one of the main factors affecting rate of gelifluction (Washburn, 1980, p. 204), and therefore the greater moisture in the drainageways would result in much higher rates of gelifluction there than on the drier interfluves, resulting in gelifluction streams on lower slopes.

Concerning possible future work, because of the alternation between young and old deposits over very short distances (e.g., Fig. 5), mapping of slope deposits of different ages on a scale of 1:24,000 is probably not feasible in this area. Even mapping on specially constructed large-scale maps would be difficult, because a ubiquitous stony surface layer makes the use of hand augers impossible. A map of boulder distributions could be constructed and would be of interest. Potentially the most informative project would be to trench young colluvial deposits at locations where they are likely to have remained saturated since late Wisconsin times, in the hope of finding datable organic material. Trenching of older deposits, although probably not useful for dating purposes, would allow better descriptions of soil profiles, weathering characteristics, and sedimentological properties.

SUMMARY AND CONCLUSIONS

Extensive sheets of colluvium cover the northwest flank of Grandfather Mountain, the southeast flank of Flattop Mountain, and other slopes in the vicinity. Logs from 13 wells drilled on the northwest flank of Grandfather Mountain showed a mean depth to bedrock of 16.7 m, which provides a limiting mean thickness for the colluvium, as part of the regolith consists of saprolite. Road cuts show that colluvium in and near modern drainage ways is relatively unweathered, whereas colluvium on interfluves generally is somewhat more weathered, although sometimes younger colluvium overlies older colluvium. Boulder deposits are confined mainly to the surfaces of younger colluvial deposits. Two topographic profiles surveyed across slope parallel to road cuts show that these relationships hold even when drainageways are only a few meters wide, interfluves a few tens of meters wide, and cross-slope relief less than 8 m.

Size analysis of the coarse fraction of the colluvium was performed at six locations by means of point-counting road cuts using a grid. The results showed a wide range in size distribution, with the mean of all six grids showing that about 60% of the clasts in the slope deposits are 8 mm or larger in size. Pebble roundness was measured at 7 sites and showed that colluvial clasts are somewhat more angular than alluvial clasts for a comparable distance of travel, suggesting that the clasts were not transported downslope by normal fluvial processes.

Relative dating of deposits was accomplished by measuring color, percent clay, and percent weathered clasts. Although percent clay showed no consistent variation, hue and percent weathered clasts successfully distinguished the younger and older colluvium. The fact that there appears to be a time hiatus between the younger and older deposits rather than a continuum suggests that deposition has been episodic, which if true suggests (but does not prove) a climatic control of colluviation. Within the older deposits, however, no additional breaks were apparent, there being a continuum from moderately to highly weathered.

Aside from the possible time gap between young and old deposits, the only other evidence suggestive of periglacial conditions is the huge volume of the colluvial and boulder deposits. No features truly indicative of periglacial conditions, however, such as patterned ground or involutions, were observed. Hence, although pollen evidence from the central and southern Appalachians makes it likely that periglacial conditions existed on Grandfather Mountain during Pleistocene glaciations, and the slope deposits are compatible with a periglacial origin, such deposits do not provide independent evidence of periglacial conditions. One possibility that should be kept in mind is that the boulders and colluvial material may have been produced under periglacial conditions, but may subsequently have been reworked by catastrophic floods, creep, and other processes associated with nonglacial climates. This would apply not only to debris produced during the late Wisconsin, but also to that produced during earlier glaciations, and could help explain the lack of periglacial features.

ACKNOWLEDGMENTS

The field work for this study was supported by a Faculty Research grant from Clemson University. I thank Mr. Skip Hartley and the GF Company for their cooperation and assistance.

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MAGNETIC SURVEY OF THE BALSAM GAP DUNITE, JACKSON COUNTY, NORTH CAROLINA*

By

F. M. Honeycutt**, R. A. Heimlich, and D. F. Palmer
Department of Geology
Kent State University
Kent, Ohio 44242

ABSTRACT

A ground magnetic survey combined with measurement of magnetic susceptibilities and geophysical modeling reveals that the Balsam Gap dunite 1) is outlined by a well-defined positive magnetic anomaly, 2) differs in areal extent and plan shape compared with the results of earlier geologic mapping, 3) has a mean magnetic susceptibility of 15.49×10^{-5} emu/cm^3 (standard deviation 25.16×10^{-5}) in contrast with 2.78×10^{-5} emu/cm^3 (standard deviation 1.10×10^{-5}) for the enclosing gneiss, 4) has a variation in magnetic susceptibility which is directly related to the degree of serpentinization (accompanied by extensive development of fine-grained secondary magnetite), 5) is pod-shaped in cross-section, and 6) has a maximum depth of 180 meters. The results of the study suggest that magnetic surveys may constitute an important tool in the exploration for refractory olivine in the gneissic terrain of the southern Appalachian Mountains, and that they should prove useful for purposes of ore estimation and mine development.

INTRODUCTION

Particularly during this time of increased demand for refractory olivine, there is considerable commercial interest in determining the areal extent and thickness of individual dunite bodies which are common in the southern Appalachian Mountains. Because of generally sparse outcrops, and the commonly thick soil and vegetative cover, the plan shape and size of many of these masses are known only approximately on the basis of geologic mapping. Although earlier studies by Hunter et al. (1942) reported low magnetic values over several North Carolina dunites in contrast with higher values over the enclosing gneisses and schists, little geophysical study has been made of them since. That which has been done (Callahan et al., 1978) has focused on determining the areal extent of the ultramafic rock. Other than a brief abstract (Greenberg, 1976), no published studies have reported information on subsurface configuration and thickness. Yet such information is invaluable with respect to mining considerations and commercial extraction of the olivine.

The lack of mafic units associated with many of these ultramafic bodies has led some authors to question whether the Southern Appalachian ultramafites were ever part of now-disrupted ophiolite sheets (Misra and Keller, 1978). The three-dimensional shapes of these ultramafite masses may furnish additional evidence as to their origin, and may provide a clue to their mode of emplacement relatve to the plate tectonics model. Elongate, steeply-plunging or irregularly shaped bodies are consistent with diapiric or tectonic emplacement of mantle material (in subduction environments) whereas tabular or sheet-like bodies are perhaps more consistent with laterally-emplaced or obducted ophiolites (Dewey and Bird, 1971; Chidester and Cady, 1972; Stevens et al., 1974).

The objective of the present study was to conduct a magnetic survey primarily of the Balsam Gap dunite, and to a lesser extent the smaller Middleton dunite, to determine size and shape in plan view and at depth. The two dunites occur in northern Jackson County, western North Carolina (Fig. 1).

*Contribution No. 193, Department of Geology, Kent State University, Kent, Ohio
**Present address: Atlantic Richfield Company, 119 E. 6th Street, Tulsa, OK 74145

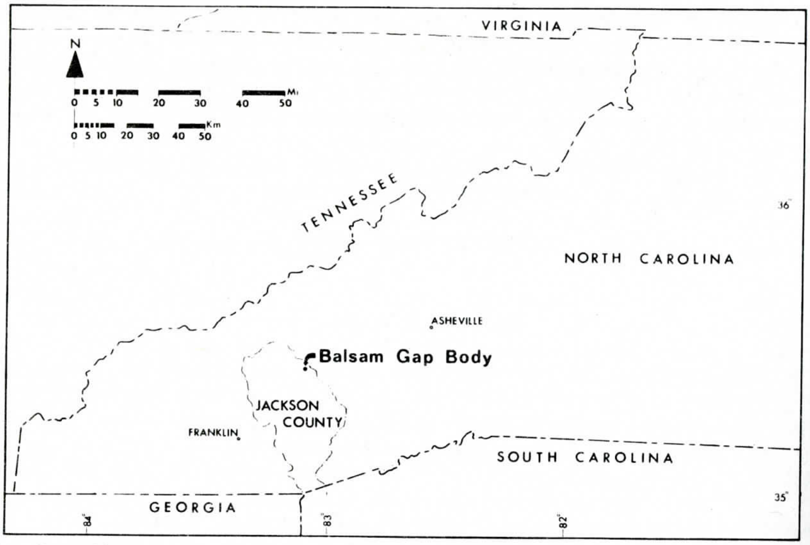

Figure 1. Location map.

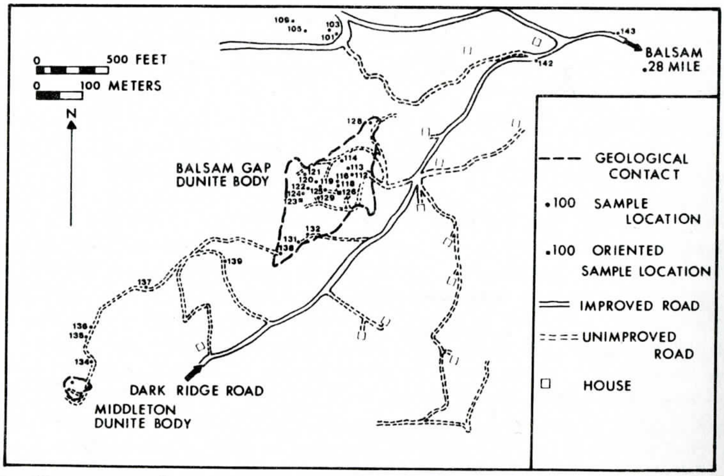

Figure 2. Outline map of the dunite bodies.

GEOLOGY

In terms of physical characteristics, geologic setting, textures, mineralogy, and lithology, the dunites appear to be representative of many of the ultramafic bodies in the southern Appalachians (Misra and Keller, 1978). The Balsam Gap and Middleton bodies are situated within a metamorphic terrain which is dominated by biotite-quartz-feldspar gneiss and hornblende-quartz-feldspar gneiss. Although outcrops are sparse (Fig. 2), petrographic study of samples from various parts of the area suggests that the rock is relatively uniform, particularly with respect to its magnetic mineralogy; total opaque oxides constitute less than 0.4% of the modes for all samples studied (Honeycutt and Heimlich, 1980).

The primary mineralogy of the Balsam Gap dunite and the Middleton dunite, to the southwest (Fig. 2), consists of magnesian olivine (Fo93) and chromite. These minerals are altered in varying degrees to assemblages which include serpentine, talc, chlorite, vermiculite, anthophyllite, calcite, tremolite and magnetite (Honeycutt and Heimlich, 1980). Modal analyses indicate that the content of secondary minerals ranges from 1.7 to greater than 40% by volume. In all samples the secondary mineral assemblage contains serpentine, commonly the dominant alteration mineral, which is characterized by disseminated tiny grains of secondary magnetite (verified by X-ray analysis). Generally the alteration increases toward the margins of the Balsam Gap body. Except for the variation in the degree of alteration, the dunite is a relatively uniform, massive rock lacking chromite segregations and later veins and dikes.

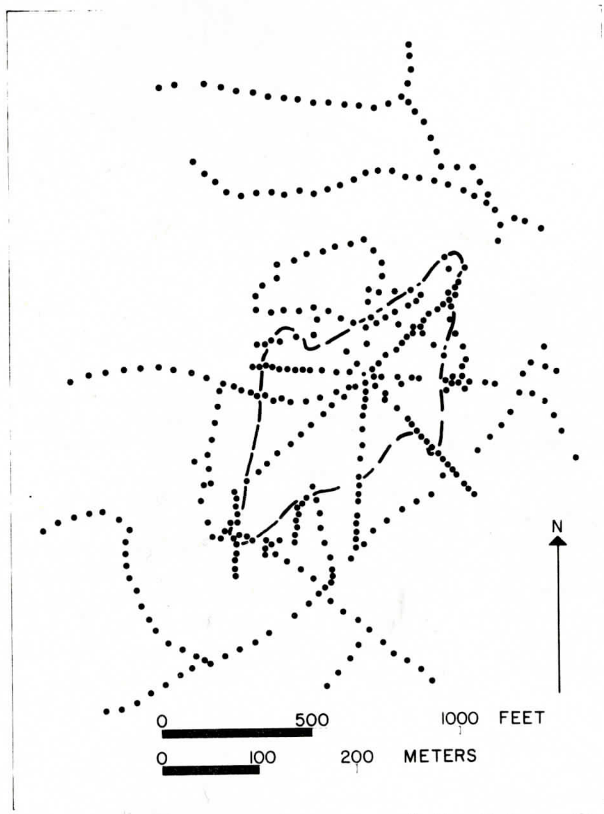

Figure 3. Station locations for magnetic survey of the Balsam Gap-Middleton area.

GROUND MAGNETIC MAP

Magnetic data were obtained with a Geometrics Portable Proton Precession Magnetometer. By means of overlapping traverses, data were collected at approximately 700 stations at 15-meter spacings (Fig. 3) and readings were taken at a central base station every hour to correct for drift. The data were then reduced, plotted, and contoured by standard methods.

The resulting map (Fig. 4) shows well-defined positive magnetic anomalies coincident with the Balsam Gap and Middleton dunites. While similar magnetic highs are associated with the Twin Sisters dunite in Washington (Thompson and Robinson, 1975), typically magnetic lows are associated with other dunites in North Carolina (Hunter et al., 1942; Callahan et al., 1978).

The magnetic data suggest that, in plan view, the long axis of the Balsam Gap body is oriented N35E, essentially coincident with the strike of foliation in the country rock (Honeycutt and Heimlich, 1980). Based on magnetic data and the shallow depth of the Balsam Gap body its maximum plan dimensions are 390 by 240 meters. The Middleton body is essentially circular in map view with a diameter of approximately 50 meters. Low amplitude contours over the gneiss generally follow the strike of its foliation.

In comparison with the original map of the Balsam Gap body (Hunter, 1941), the magnetic data indicate a plan size approximately 60% less than that based or field

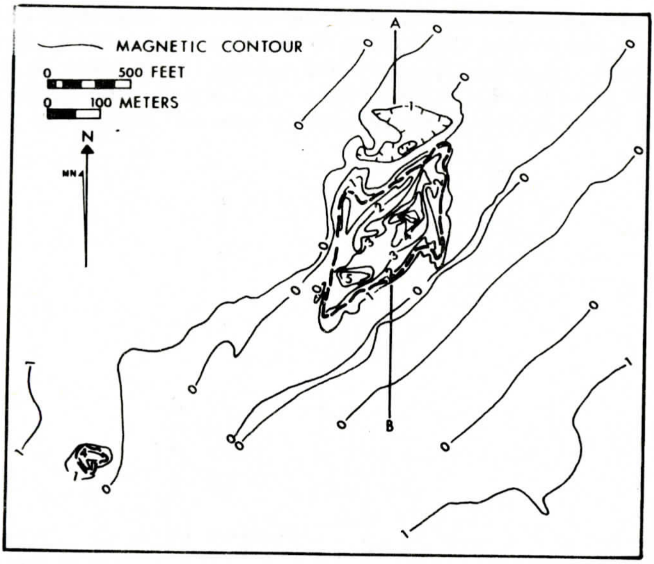

Figure 4. Ground magnetic map of the Balsam Gap-Middleton area. Contour interval 100 gammas; base value 54,400 gammas.

mapping exclusively (Fig. 5). Apparently several major areas of dunite, previously mapped as outcrop, are large float blocks located downslope from the body. Although comparable in areal extent to that determined by Astwood et al. (1972), the map outline of the body, based on field mapping combined with magnetic surveying in this study, is different from its outline as mapped in both earlier studies (Fig. 5).

The coupling of a negative magnetic anomaly north of the major positive anomaly along profile A-B (Fig. 4) suggests that the observed anomaly is induced as a function of the magnetic susceptibility contrast between the country rock and the dunite.

MAGNETIC SUSCEPTIBILITY MEASUREMENTS

By means of a Soiltest Magnetic Susceptibility Bridge, the suceptibility was measured for samples of both the dunite and the gneiss (Table 1). On the basis of seven samples, mean susceptibility for the gneiss was determined to be 2.78×10^{-5} emu/cm^3 with a standard deviation of 1.10×10^{-5}. This value compares closely with measurements of susceptibility (2.44×10^{-5} emu/cm^3) for other samples of gneiss in the area (Schiering, Heimlich and Palmer, 1981). The low bulk susceptibility of the gneiss is consistent with the observed low oxide content of this rock.

The mean susceptibility of the dunite, based on 12 representative samples, is 15.49×10^{-5} emu/cm^3, with a standard deviation of 25.16×10^{-5} which reflects the large variations found in this body. Susceptibilities for weakly altered dunite are expected to be low, due to the small content of magnetite. The susceptibility of the dunite increases in direct proportion to the percentage of serpentine in the modes (Table 1). Alteration to talc, chlorite, and tremolite is not accompanied by the development of magnetite in the same way that serpentinization is. Very fine grains of magnetite (distinguished from chromite by X-ray analysis) are found throughout the serpentine. Although they are generally too small to be reflected in the modal analyses, they are present in a considerably large aggregate volume. The magnetite develops from the alteration of the olivine (which contains 8-10% Fe_2SiO_4) to serpentine. The serpentine admits little of this iron into its atomic structure (Whittacker and Wicks, 1970; Wicks and Whittacker, 1977) and in the absence of other iron-bearing alteration products, magnetite develops. On the basis of mass balance alone, one would expect a large amount of fine magnetite to develop by this mechanism. Its presence is indicated in the extremely high susceptibility values found in some of the more altered dunite samples (Table 1). Our data support the findings of

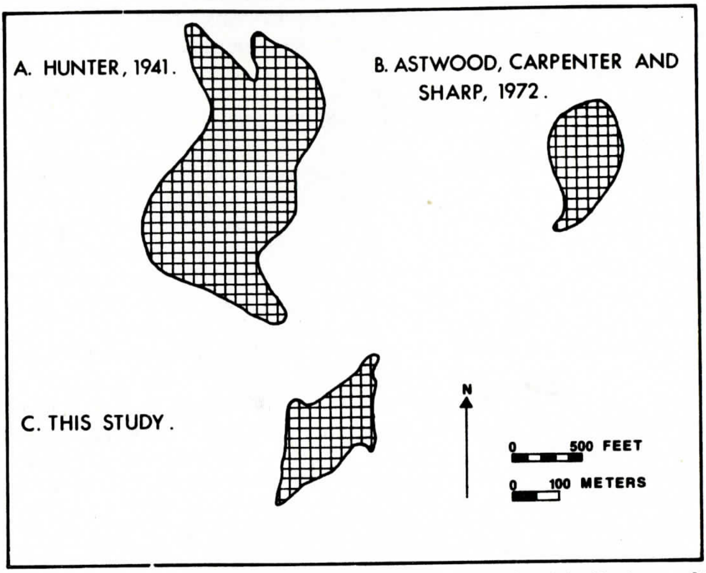

Figure 5. Earlier maps of the Balsam Gap body compared with that resulting from the present study.

Table 1. Magnetic susceptibility measurements on samples from the Balsam Gap dunite and adjacent gneiss.

SAMPLE NUMBER	DUNITE	DEGREE OF SERPENTINIZATION*	GNEISS	MAGNETIC SUSCEPTIBILITY**
120	X	1.7		1.57×10^{-5}
116	X	2.6		2.43×10^{-5}
118	X	2.6		2.94×10^{-5}
138	X	2.9		3.08×10^{-5}
128	X	3.4		4.44×10^{-5}
123	X	3.4		4.82×10^{-5}
125	X	4.1		5.91×10^{-5}
129	X	5.4		4.10×10^{-5}
132	X	5.9		3.10×10^{-5}
121	X	6.7		15.98×10^{-5}
113	X	33.8		68.10×10^{-5}
112	X	39.6		69.40×10^{-5}
		MEAN FOR DUNITE		15.49×10^{-5}
		Standard Deviation		25.16×10^{-5}
101			X	1.87×10^{-5}
105			X	2.30×10^{-5}
134			X	1.91×10^{-5}
137			X	3.06×10^{-5}
139			X	3.44×10^{-5}
142			X	1.99×10^{-5}
143			X	4.87×10^{-5}
		MEAN FOR GNEISS		2.78×10^{-5}
		Standard Deviation		1.10×10^{-5}

*Modal percent serpentine
**emu/cm^3

Saad (1969), for dunites and serpentinized peridotite from Red Mountain (California), that larger positive magnetic anomalies should be associated with the more serpentinized parts of ultramafic bodies.

The western North Carolina ultramafites have a very weak positive NRM (Perez, 1979); Penso, 1981), and thus the primary cause of the magnetic anomalies observed is the variation in the magnetic susceptibilities of the rocks in the area. Comparison with the work of Thompson and Robinson (1975) on the Twin Sisters dunite suggests that the component of the total field due to the NRM will be very minor (perhaps as low as 2%, but no more than 7%) in relation to the induced magnetism. Thus the fact that we have neglected the absolute magnitude of the NRM component in this study should not greatly affect the magnetic models we have constructed.

MAGNETIC MODELING

Magnetic modeling was done using the Burroughs 6800 and Hewlitt-Packard 9845S computers at Kent State University, with programs written in house. Computations were based on standard equations for total field and vertical anomalies (Telford et al., 1977; Dobrin, 1976). The basic form of the body first was determined by comparison of the observed anomaly with computed values for simple geometric forms such as a sphere, slabs, and cylinders. Of these, the best fit was found to be that of a sphere, suggesting that the body is approximately equant to ellipsoidal with a definite floor.

Further calculations involved two-dimensional modeling of modified prismatic sections and of stacked slabs using standard equations (Telford et al., 1977; Dobrin, 1976). The stacking of these shapes allowed continuous feedback between the calculated anomalies and the observed anomaly so that we could gradually construct a shape which was consistent with the data. The two approaches--prismatic (Fig. 6) and slab (Fig. 7)--allowed us the ability to assess the similarities in the models from two different starting points. Both models use a k of 5×10^{-4} emu/cm^3 and suggest essentially the same kind of pod-shaped body extending to a maximum depth of 180 meters. The prismatic model (Fig. 6) shows the body to plunge approximately 60^o north. Although suggesting the same shape, the stacked slab model fails to show the same definite plunge.

Two problems were incurred during the modeling process. The first concerned the apparent variation in magnetic susceptibility between the surface and subsurface rock. Measured susceptibilities of surface samples are on the order of 10^{-4} emu/cm^3, but the subsurface ultramafic rock appears to have a magnetic susceptibility closer to 10^{-3} emu/cm^3 based on matching of the amplitude of the calculated anomaly to that of the observed anomaly, even with corrections for finite strike length (Telford et al., 1977). Based on the relationship between serpentinization and increased magnetic susceptibility, this suggests that the lower sections of the body may be enclosed in a sheath of serpentinized dunite similar to the lower section of the Twin Sisters dunite (Thompson and Robinson, 1975).

The second problem involved the fact that the body crops out as a conical hill approximately 30-40 meters high. To compensate for this topographic effect, several thin slabs were added to the top of the prismatic model. Similarly, several thin slabs were added to the bottom of the prismatic model to adjust the calculated anomaly so as to better fit the observed anomaly. The simpler model of the stacked slab was constructed by summing the anomalies of a sequence of stacked slabs (Telford et al., 1977). By shifting the positions of the slabs of different thickness and length, the calculated anomaly shown in Figure 7 was achieved.

Both approaches to the modeling yielded essentially the same geologic interpretation. The body is approximately equant to ellipsoidal in both plan view and in cross-section, although in map view it is clearly irregular in shape with small lenses or pods which extend from the main body. While it is not possible to define these pods in the vertical direction, we believe that they may exist and may account for the slight missmatch between the observed and both calculated anomalies along the southern portion of the body. It is likely that a small extension of the dunite exists in this region at depth. Thus the body is neither diapiric nor part of a single slab, but appears to be a rounded pod with some small extensions, whose longest dimension is approximately parallel to the structure of the surrounding gneiss.

The existence of elongated extensions off of the main body suggests the possibility either of intrusive apophyses into the country rock or of sections sheared from the main mass during deformation. In view of the lack of clear high-temperature effects which should be expected where a dunitic magma intrudes quartzofeldspathic gneiss, we favor the latter interpretation. Such a conclusion is consistent with the general field relationships and with petrofabric data which suggest that some of these bodies have been reoriented during or after emplacement (Greenberg, 1976; Dribus et al., 1981).

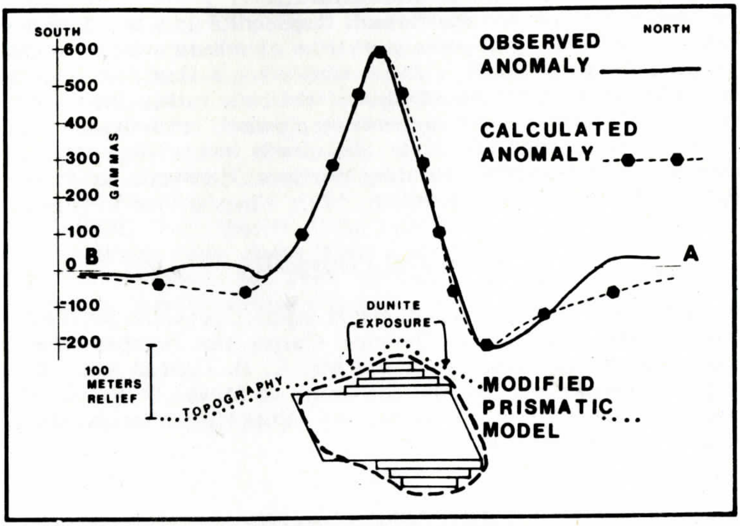

Figure 6. Modified prismatic model along profile A-B.

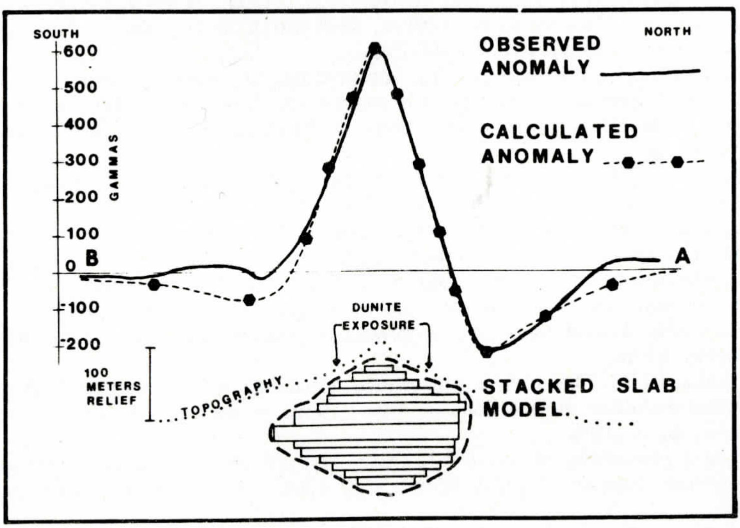

Figure 7. Stacked slab model along profile A-B.

An alternate hypothesis is based on the fact that the magnetic susceptibility is strongly related to the amount of serpentinization. Thus it is possible that the body is somewhat more regular but that the apparent extensions coincide with more extensive serpentinization along zones within the dunite. These zones are apparently sufficiently continuous to be related to planes of shear within the body. Even in this latter case, the dunite body cannot be significantly larger than we have indicated. Petrographic examination shows the overall mass to be rather homogeneous and the outcrop data do conform to the magnetic field data and the resultant models.

CONCLUSIONS

The results of this study suggest that magnetic surveys may be useful for deducing the map size and thickness of poorly-exposed serpentinized dunite bodies within the gneisses of the southern Appalachian Mountains. As such they may facilitate the exploration for refractory olivine within this area, and they should prove useful for purposes of ore estimation and mine development.

The plan shape deduced for the Balsam Gap dunite is that of an elongate body whose long axis is essentially parallel to the strike of foliation in the enclosing gneiss. In three dimensions the body is not a simple diapir nor a slab. Its shape is consistent with tectonic emplacement and reorientation of the body rather than with an intrusive igneous origin. The former emplacement mechanism is indicated by petrofabric measurements which show that this body and others in the region have a tectonite fabric independent of that in the enclosing gneisses (Honeycutt and Heimlich, 1980; Sailor and Kuntz, 1973; Hahn and Heimlich, 1977; Kingsbury and Heimlich, 1978).

ACKNOWLEDGMENTS

We are particularly grateful for financial support provided by the Society of the Sigma Xi. International Minerals and Chemical Corporation granted permission to work on the Balsam Gap dunite property as did Mr. E. B. Conrad and the Parks family relative to adjacent properties. Special thanks go to Steven P. Yurkovich, of Western Carolina University, Donald R. van Buskirk, and James Kluttz for assistance and advice during the course of the field work.

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